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SPACE BIOLOGY INITIATIVE PROGRAM DEFINITION REVIEW

TRADE STUDY 2

PROTOTYPE UTILIZATION IN THE DEVELOPMENT OF SPACE BIOLOGY HARDWARE

FINAL REPORT

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FOREWARD

This study, entitled "Prototype Utilization in the Development of Space Biology Hardware", was performed under a subcontract to Horizon Aerospace. It is one of six studies performed as a part of the NASA Space Biology Initiative (SBI) Definition Review Trade Studies Contract.

The study was performed under the direction of Mr. Neal Jackson and Mr. John Crenshaw of Horizon Aerospace and was conducted by Mr. H. J. Wood, Jr. and Mr. Arthur E. Schulze of the Biomedical Technologies Division of Lovelace Scientific Resources, Inc., Houston, Texas.

Management and engineering review were provided by the staff at Lovelace in Albuquerque, New Mexico.

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ACRONYMS AND ABBREVIATIONS

AI	Artificial Intelligence
BIT	Built In Test
BITE	Built In Test Equipment
BMMD	Body Mass Measurement Device
BPMS	Blood Pressure Measuring System
BPMU	Blood Pressure Measuring Unit
CFE	Contractor Furnished Equipment
CDR	Critical Design Review
CDTR	Cassette Data Tape Recorder
CHeCS	Crew Health Care System
COTS	Commercial Off-The-Shelf
DFI	Development Flight Instrumentation
DMS	Data Management System
DPA	Destructive Physical Analysis
DVTU	Design Verification Test Unit
ECF	Exercise Countermeasure Facility
ECG	Electrocardiograph
EDCO	Extended Duration Crew Operations
EEE	Electrical, Electronic and Electromechanical
EM	Engineering Model
EMG	Electromyograph
EMI	Electromagnetic Interference
ESA	European Space Agency
FMEA	Failure Modes & Effects Analyses
FRR	Flight Readiness Review
GAMS	Gas Analyzer Mass Spectrometer
GFE	Government Furnished Equipment
GSE	Ground Support Equipment
HMF	Health Maintenance Facility
ISO	International Standard Organization
JSC	Johnson Space Center
KSC	Kennedy Space Center
LBNPD	Lower Body Negative Pressure Device
LSE	Laboratory Support Equipment
LSLE	Life Sciences Laboratory Equipment
LSRF	Life Science Research Facility
MIL-STD	Military Standard
MCOTS	Modified Commercial Off the Shelf
NASA	National Aeronautics and Space Administration
NSTS	National Space Transportation System

OSSA	Office of Space Science and Applications
OTS	Off-The-Shelf
PDR	Preliminary Design Review
PFM	Protoflight Model
PI	Principal Investigator
PMS	Physiological Monitoring System
Qual.	Qualification
R&QA	Reliability and Quality Assurance
RF	Radio Frequency
RMS	Remote Manipulator System
SBI	Space Biology Initiative
SEU	Single Event Upset
Spec.	Specification
SRM&QA	Safety, Reliability, Maintenance & Quality Assurance
SSAEPL	Space Station Approved EEE Parts List
SSF	Space Station Freedom
SSP	Space Station Program
STS	Space Transportation System
TBD	To Be Determined
TU	Training Unit
VOCC	Venous Occlusion Cuff and Controller

Glossary and Definitions

From JSC 31000, Vol. 1, Rev. D, Appendix B

ACCEPTANCE TEST: Formal testing conducted to determine whether or not an item satisfies its acceptance criteria and to enable the user to determine to accept or reject same. Required on an end item where quantitative data is a prerequisite to demonstrate compliance of the item with design/procurement specifications.

ACCEPTANCE TESTING: 1) Formal tests conducted to assure equipment meets contracted or design requirements. Includes performance demonstrations and environmental exposures to screen out manufacturing defects, workmanship errors, incipient failures, and other performance anomalies not readily detectable by normal inspection techniques or ambient functional tests. 2) Tests to determine that a part, component, subsystem, or system is capable of meeting performance requirements prescribed in the purchase specification or in other documents specifying adequate performance capability for the item in question. Anomalies not readily detectable by normal inspection techinques or through ambient functional tests.

ADVANCED DEVELOPMENT PROGRAM: A program which focuses emerging generic technologies toward a space station application, builds and integrates prototype components into subsystems for demonstration in ground-based test bed facilities, and conducts flight experiments using the Shuttle as necessary.

ALGORITHM: Mathematical steps used in the process of solving a problem. The objectives of the algorithm is to produce a desired result (output) from specified input.

ARTIFICIAL INTELLIGENCE: 1) A subfield of computer science dealing with concepts and methods of symbolic inference by a computer and the symbolic representation of knowledge used in making inferences to make a machine behave in ways humans recognize as "intelligent" behavior. 2) A discipline devoted to developing and applying computational approaches to intelligent behavior. Also referred to as machine intelligence or heuristic programming.

ASSEMBLY: A number of parts, or subassemblies and/or any combination thereof, joined together to perform a specific function

and capable of disassembly. The distinction between an assembly and a subassembly is determined by the individual application. An assembly in one instance may be a subassembly in another, where if forms a portion of an assembly.

COMMERCIAL PART OR ITEM: A part or item which is manufactured primarily for the commercial rather than the government market and having both commercial and government applications. Commercial parts also include parts which are manufactured in accordance with normal commercial quality controlled production runs which meet or exceed the requirements of government specifications or standards.

COMMON ELEMENTS: Equipment items or subsystems that are interchangeable.

COMMON EQUIPMENT: Any equipment that can be utilized at more than one operational site.

COMPONENT: 1) A major functional entity within a susbystem which can contain both hardware and software subcomponents which can be either collocated or physically distributed within the Space Station Program element. 2) A particular hardware item within a system (e.g., a pump, valve within pump, electrical power distribution box). 3) A combination of parts, devices and structures, usually self-contained, which performs a distinctive function in the operation of the overall equipment or system (e.g., transmitter, cryogenic pump, encoder).

CONTRACTOR: The supplier of the end item and associated support items to the Government under the terms of a specific contract.

CONTRACTOR-FURNISHED EQUIPMENT (CFE): CFE is equipment provided to NASA by a prime contractor whose activities are monitored directly by a NASA program or project office.

DELIVERABLE: An item of hardware, software, or documentation which the contractor is required to deliver to the government.

DESTRUCTIVE PHYSICAL ANALYSIS: Analysis of EEE parts to assure that the internal construction, quality, and condition of samples do not vary from lot to lot.

DEVELOPMENT TESTS: Tests performed with minimum rigor and controls to substantiate a design approach. Includes tests performed to minimize technical risks and to assist design engineering activities. They encompass material selection, design tolerance verification, and identification of operational characteristics.

ENVIRONMENTAL TEST: Any test performed under environmental conditions other than ambient for the primary purpose of verifying the quality of the GSE.

EXPERIMENT: The system of hardware, software, and procedures for performance of a scientific or applications investigation undertaken to:
--Discover unknown phenomena
--Establish the basis of known laws
--Evaluate applications processes and/or equipment

FAILURE MODES AND EFFECTS ANALYSIS (FMEA): Identification and evaluation of what items are expected to fail and the resulting consequences of failure.

FAULT TOLERANCE: 1) The ability to continue to operate in the presence of anomalies or failures. 2) The number of failures which can be allowed without disruption of nominal functional performance.

GOVERNMENT-FURNISHED EQUIPMENT: Equipment in the possession of or acquired by the Government, and delivered or made available to a non-government organization.

LIFE CYCLE COSTS: A process and technique for predicting and considering the entire cost of a program or project from inception to ultimate disposition.

LIMITED LIFE: An equipment item or system is designated as having a limited useful life in relation to its application. Limited life includes operating time or cycles and age life.

LIMITED-SHELF-LIFE ITEM: Any item which deteriorates with the passage of time and thus requires periodic replacement, refurbishment, retesting, or operation to assure that its operating characteristics have not degraded beyond acceptable limits. This includes installed as well as stored components.

LONG LEADTIME ITEMS: Those items which because of their complexity of design, complicated manufacturing processes, or limited production, may cause production or procurement cycles which would preclude timely or adequate delivery, if not ordered in advance of normal provisioning.

OFF-THE-SHELF DESIGN: An existing design for equipment with known characteristics and proven history that has not been manufactured for which product enhancement changes could be incorporated into its production.

OFF-THE-SHELF EQUIPMENT: Equipment of an existing design that has already been completely manufactured and is already for delivery.

OFF-THE-SHELF HARDWARE: Production or existing design hardware (black box, component) used in or for NASA, military, and/or commercial programs.

OPERATING LIFE: The maximum operating time or cycles which an item can accrue replacement or refurbishment without risk of degradation of performance beyond acceptable limits.

PART: One or more pieces joined together which are not normally subject to disassembly; it maybe deviated, EEE, or substituted.

Deviated Parts--Parts deviating to some degree from their controlling specifications.

EEE Parts--Devices such as transistors, diodes, microcircuits, resistors, capacitors, relays, connectors, switches, transformers and inductors which are in compliance with the NASA Standard Parts List MIL-STD-975.

Nonstandard EEE Parts-- A EEE part not listed in MIL-STD-975, NASA Standard EEE Parts List or SSAEPL.

Grade 1.--The classification used for higher quality standard parts intended for applications that the responsible NASA project office has determined to be critical.

Grade 2--The classification used for inclusion within the applicable standard and are intended for applications not requiring Grade 1 parts.

Substitute Parts-- Parts differing from those specified in the approved equipment design.

PROTOFLIGHT: A verification activity using flight hardware and software for ground qualification in lieu of a dedicated test article. The approach includes the use of reduced test levels and/or durations and post-test hardware refurbishment where required.

PROTOFLIGHTING: The programmatic process of manufacturing a singular item, using it for verification and limited (nondestructive) testing, refurbishing it as required, and then using it as a flight article.

PROTOTYPE: A hardware item having essential features of a production unit, but differing in certain respects, such as packaging and weight. It is used to support test activities, and to demonstrate manufacturing techniques, but is not used for flight.

QUALIFICATION TESTS: Tests conducted as part of the certification program to demonstrate that design and performance requirements are realized under specified conditions.

REDUNDANCY: The existence of more than one means for performing a given function.

RELIABILITY: The probability that a system or product will perform in a satisfactory manner for a given period of time when used under specified operating conditions.

REPAIR PARTS: Individual parts or assemblies required for the maintenance or repair of equipment, systems, or spares. Such repair parts may also be repairable or nonrepairable assemblies, or one-piece items. Consumable supplies used in maintenance or repair such as wiping rags, etc., are not considered repair parts.

RISK: 1) The probability of suffering harm or loss. 2) The chance (qualitative) of loss of personnel, loss of system or damage to, or loss of equipment or property.

SOFTWARE VALIDATION: Tests and/or analyses to determine that software design meets requirements:

A. Validation by Testing-- The process of conducting tests to prove the software design meets established design requirements.

B. Validation by Analysis--1) Analysis performed to show a software article previously validated is reused or recovered (modified) to perform a similar function. 2) Analysis performed to satisfy validation objectives when testing under simulated mission conditions is not feasible or cost-effective or the need exists to extrapolate test data beyond the performed points.

SPARE PARTS: Components, assemblies, and equipment that are completely interchangeable with like items installed or in use which are or can be used to replace like items removed during maintenance and overhaul.

SPARE(S): An item or items whose fit, form and functions are completely interchangeable with another or like item or items. Types of spares for the SSFP are identified as: (1) development spare parts, (2) initial spare parts, and (3) replenishment spare parts.

SPARING: The act of quantifying and identifying spares and associated parts required to support an item or total system (e.g., control moment gyros--two spares).

SPECIFICATION: Document or combination of documents controlling the design parameter (i.e., materials used, physical and electrical characteristics.

SUBASSEMBLY: Two or more parts which form a portion of an assembly or a component replaceable as a whole, but having a part or parts which are individually replaceable (e.g., telephone dial, mounting board with mounted parts, etc.).

SUBSYSTEM: A specific set of hardware and/or software functional entities and their associated interconnections, which perform a single category of functions (e.g., data storage and retrieval subsystem, video subsystem). The functional level immediately below the "system" level.

VERIFICATION: A process which determines that Space Station hardware and software systems meet all design, performance, and safety requirements. The verification process includes analysis, test, inspection, demonstration, or a combination thereof.

The two levels of verification activities include:

A. Hardware/Software Verification Activities--A process to ensure specific hardware/software is built in accordance with the design, meets established performance requirements and is free of manufacturing and workmanship defects.

B. Design Verification Activities--A process to ensure design of the Space Station, subsystems, or components as designed and meets requirements defined in contractual specifications. They include both formal certification and system-level verification activities (including hardware/software and interface compatibility). Where verification is not accomplished by testing, analysis is to be performed.

EXECUTIVE SUMMARY

TECHNICAL FACTORS: Examination of the past and present prototype hardware development activities has disclosed that there are a number of valuable lessons to be learned from NASA's experience as well as from that of a number of other industry and government groups. In addition to the outlined approaches to the construction and use of protytypes and the identification of the driving factors, major findings are related to the impact of component and system obsolescence, shortened time of support by part manufacturers, the reduced number of part manufacturers, and the resulting non-availability of replacement parts. These findings all impact the planning for SBI Hardware prototypes.

It is shown that adaptation of modified commercial off-the-shelf hardware has distinct advantages over new starts in the areas of reduced cost and greater design maturity. Experience shows that the adaptation must be done methodically and with great skill by persons having extensive previous experience.

Many technical details for successfully implementing prototype development programs are presented. They cover full hardware development from a new start as well as development based on modification of commercial off-the-shelf hardware.

The possible applications of each type of prototype article are examined and the major program value of each identified. The limits to apparent cost advantages and the increased risk of the "protoflight" hardware approach are discussed as well as the continued need for an engineering unit within the program.

PROCEDURES: The various methods of developing prototype hardware have been combined and simplified into an integrated sequence of steps which define a recommended approach for each set of circumstances. Using the flow chart procedure presented, one determines a reference set of required hardware units. Then, by considering the parameters identified in a family of "drivers", the starting quantities are driven down or up to match them with the particular programmatic application.

RECOMMENDATIONS: A number of items are identified and discussed which, if uncorrected, will drive up costs and reduce the number of potential prototype hardware suppliers supporting NASA.

Ten major areas of concern are highlighted in the Recommendations (Section 3.0) of this report.

CONCLUSIONS: The major conclusions of this trade study are summarized in Section 4.0.

1.0 INTRODUCTION

1.1 BACKGROUND

The factors that should be used by designers and planners of space hardware to determine the number and types of prototypes required to successfully conduct a biomedical research program are overwhelmingly numerous. Organized decision-making requires subdivision of the problem such that it can be attacked in reasonable, digestible pieces.

The prototyping activities to be considered in this study range from no prototypes where a single unit serves as a flight unit, often called a "protoflight", to multiple prototypes for each function; i.e., concept unit, reliability unit, DVTU unit, training unit, back-up unit, etc. Prototyping fits into a phase of system engineering which can nominally be called "evaluation." (Machol, 1965)

The evaluation phase should determine whether the performance of a system is adequate to fulfill the operational mission assigned to the system. In a well-managed development program, the evaluation is conducted throughout the design phase and is "largely completed before the prototype is constructed." "It therefore follows that evaluation should be largely completed before the really expensive phases of prototype construction and test are undertaken." (Machol, 1965)

The following definitions apply to the various terms as used in this study:

ENGINEERING PROTOTYPE: "A hardware item having essential features of a production unit, but differing in certain respects such as packaging and weight." Prototypes are "used to support test activities and to demonstrate manufacturing techniques, but are not used for flight."

PROTOFLIGHTING: "The programmatic process of manufacturing a single item, using it for verification and limited (nondestructive) testing, refurbishing as required, and then using it as a flight article." (For purposes of this study, a protoflight unit is considered a flight unit and not a prototype).

RELIABILITY: "Distribution of failures in the time domain"

QUALITY CONTROL: "Distribution of defects in a population"

OPERATION: "Activity resulting from the use of systems."

Some of the terms commonly used to refer to prototypes of aerospace subsystems are as follows:

1. Breadboard
2. Proof of Concept Model
3. Brassboard
4. Pre-Production Model
5. Mock-Up (Not necessarily a "prototype")
6. Design Verification and Test Unit (DVTU)
7. Training Unit
8. Qualification Test Unit
9. Engineering Model
10. Thermal Test Article

These items are often semantically intertwined and mock-up units are not necessarily operational prototypes--the need for mock-ups is usually independent of the need for prototypes. Mock-ups are usually non-functioning units used for a multitude of purposes. Generalized drivers to define the number and types of mock-ups are uniquely programmatic and are not a part of this study.

Analyses of the naming of prototypes have shown that the fundamental categories might be listed in the order of increasing fidelity as follows:

1. Breadboard ("Commercial Off The Shelf Unit")
2. Brassboard (Proof of Concept Model)
3. Design Verification and Test Unit (DVTU) (Engineering Model)
4. Training Unit
5. Qualification Unit (Pre-Production Unit)

Even these fundamental prototypes can have double and triple uses; e.g., a DVTU might be used as a Qualification Unit and/or Back-Up Flight Unit. Obviously, computer simulation might even be used for some hardware to eliminate the need for the lower level prototypes. (Hopcroft, 1988)

Definitions and conventional uses for these units are as follows:

BREADBOARD: A breadboard is the first experimental combination of hardware, and in some cases software, developed in a sequence of progressively more complex prototype units. It may consist of a group of standard test equipment, together with various experimental circuits. It is used to demonstrate a concept and to investigate or optimize various functions. Most digitial and some analog circuit development is suitable for computer simulation rather than hardware experimentation.

BRASSBOARD: A brassboard is a hand-crafted prototype unit which usually incorporates all electronic elements of the final article. Its configuration allows assessment of effects such as mutual circuit interactions and distributed capacitance. Realistic computer simulation of this evaluation unit is difficult to achieve. This prototype is particularly useful in the evolution of radio-frequency and high speed digital systems. It is often the first opportunity to confirm anticipated interface compatibility.

DESIGN VERIFICATION TEST UNIT (DVTU) OR ENGINEERING MODEL (EM): This prototype may be called either name. It is essentially identical, both mechanically and electrically, to the flight article except that it is assembled with commercial, rather than high-reliability, parts. All design changes should be incorporated and evaluated on this unit. Compatibility, software performance, and all functional tests should be accomplished with this prototype. It should also be subjected to extensive environmental tests. One of the most valuable aspects of the DVTU or EM is that it normally allows methodical analysis of the device and completion of all design changes prior to the activation of rigorous formal SRM&QA documentation procedures necessary for all subsequent activities.

QUALIFICATION UNIT: A qualification unit is the highest quality prototype. It is absolutely identical to the flight hardware and software in every respect. Ideally, it is reserved for formal testing which verifies that the system or device meets all requirements and specifications. Normally this system is not flown since it has been exposed to higher than flight environmental test levels. The exception is in a protoflight program where only one flight-configured article is built, qualification tested, and flown. Every aspect of the life of this unit is under strict procedural and documentation control.

MOCKUP: Mockup units are not operational prototypes but they demonstrate some particular attribute of the flight article and thereby provide valuable support in design and application testing. Typical evaluation activities include thermal and cooling tests, mass distribution tests, mechanical interface tests, and human factors evaluations.

PROTOFLIGHT MODEL: (PFM) Under the protoflight concept, only one unit is built using flight standard high-reliability parts. This protoflight model combines the normal prototype and flight models in some cost-critical applications. The protoflight model should be preceded by a development/engineering model in order to allow completion of all changes and engineering tests prior to fabrication of the qualification/flight unit.

TRAINING UNIT: A training unit is a prototype article which is normally dedicated to flight crew training. It should be physically and functionally like the flight articles. In some cases, the engineering model is used for this purpose. Nominal control procedures apply to the unit unless it is designated a flight or spare unit, in which case stringent SRM&QA procedures will apply.

The overriding reason for constructing engineering prototypes is to provide "early warning of potential operational problems." (Machol, 1965). Other primary reasons are as follows:

1. Verify that operational performance meets design specific specifications
2. Determine the effects of extreme environments
3. Assess reliability for extended periods of operation
4. Determine the effects of component tolerance and variability on overall system performance

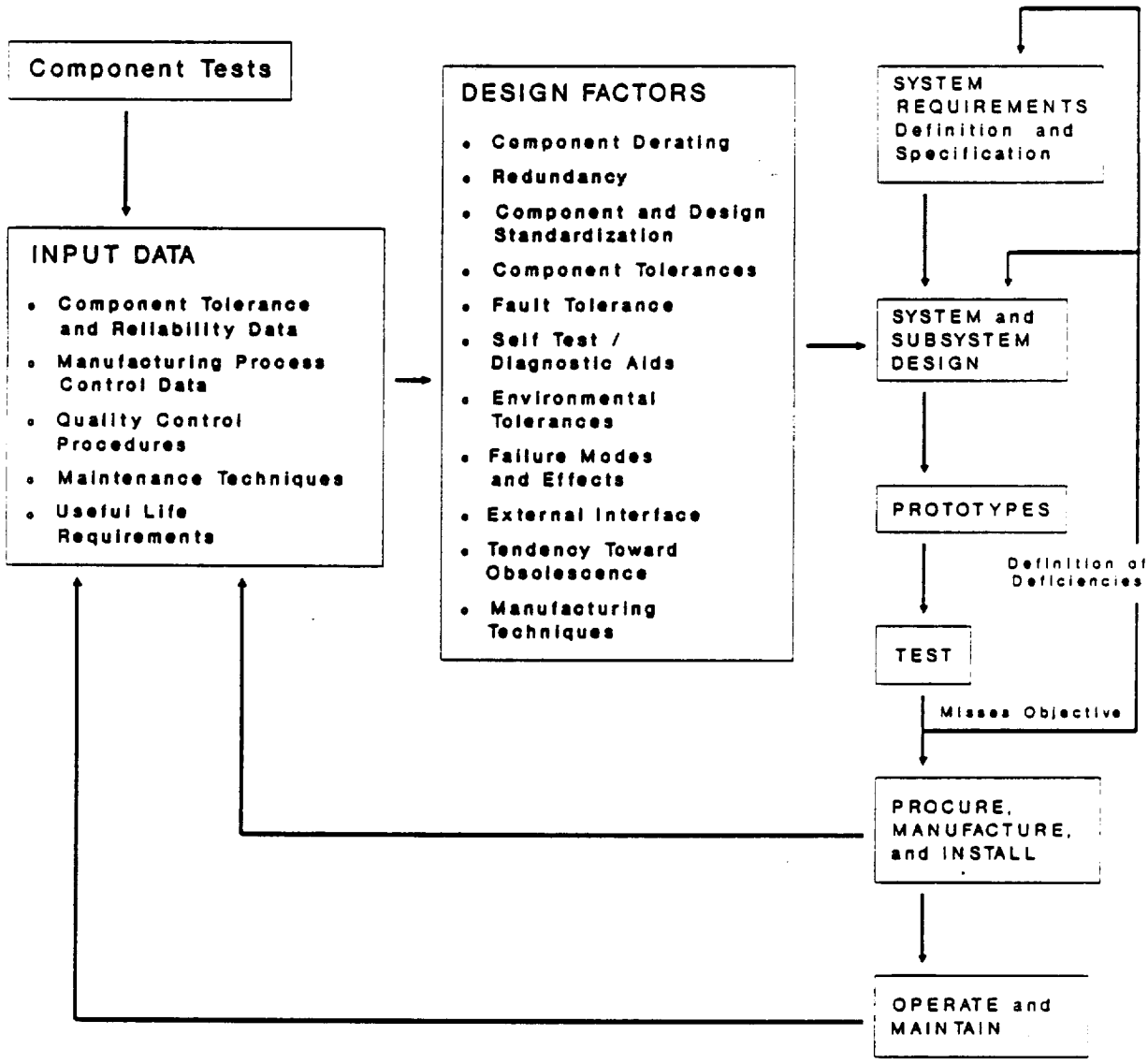
Some of the secondary uses of prototypes are as follows:

1. Train operators and maintenance personnel
2. Demonstrate system performance to users and management
3. Debug system interfaces and software
4. Evaluate the EMI emission and susceptibility

Figure 1.1-1 is a diagram which illustrates the role of prototypes in the system disign process. The importance of a strong prototyping program to the successful completion of an iterative design program is obvious.

Figure 1.1-1

ROLE OF PROTOTYPES IN THE SYSTEM DESIGN PROCESS



[From Machol, 1965]

1.2 PURPOSE

The objective of this study was to define the factors which space flight hardware developers and planners should consider when determining:

1. Number of hardware units required to support program
2. Design level of the units
3. Most efficient means of utilization of the units

The analysis considered technology risk, maintainability, reliability, and safety design requirements for achieving the delivery of highest quality flight hardware. Relative cost impacts of the utilization of prototyping were identified.

1.3 METHODOLOGY

Numerous sources of information on the utilization of prototypes for the development of commercial hardware, space flight, research hardware, and industrial hardware have been surveyed by literature searches, personal interviews, and telephone interviews. The following sources provided a significant input for this study:

1. NASA past experience (Skylab, Spacelab, etc.)
2. Similar Shuttle requirements/experience
3. Experience of other programs (JPL Deep Space, communications satellites, DOE, etc.)
4. Industrial experience (medical implants, downhole instrumentation, etc.)
5. Space Station requirements already defined
6. Software development experience of similar programs

Case studies of past and present NASA hardware development experience have supplied considerable information describing the proper use of prototypes in the research hardware development process. The following NASA Life Sciences hardware programs provided insight into the prototype development process:

Blood Pressure Measuring Unit	(BPMU)	
Blood Pressure Measuring System	(BPMS)	(Skylab)
Physiological Measuring System	(PMS)	

Electromyograph Signal Conditioner	(EMG)
Electrocardiograph Signal Conditioner	(ECG)
Minicentrifuge	
Body Mass Measuring Device	(BMMD)
Gas Analyzer Mass Spectrometer	(GAMS)
Cassette Data Tape Recorder	(CDTR)
Skylab Refrigerator/Freezer	
Orbiter Refrigerator/Freezer	
Baro Experiment Neck Cuff	
LSLE Microcomputer	

Large quantities of telecommunications equipment have been developed by NASA/JSC and supplied as GFE to the manned space flight programs. This equipment is similar in many respects to the SBI hardware and the experience of these engineers and managers in GFE hardware should be of direct applicability to SBI. The following representative samples of this hardware were considered from the prototype development standpoint:

Hardware	Program	Proto. Method
DFI Telemetry	Apollo GFE	Shelf & Dev.
Lunar Comm Ry	Apollo GFE	New Dev.
AF Tape Player	Apollo GFE	Mod. Off-Shelf
TV Systems	Apollo & STS GFE	New Dev.
Signal Process	STS GFE	New Dev.
Teleprinter	STS GFE	Mod. Off-Shelf
Text & Graph	STS GFE	Dev/Shelf Tech.
Cabin Leak Det	STS GFE	Off-Shelf
Sir-C Payload	STS GFE	Off-Shelf Mod/ Internat'l. Dev.

Representative personnel from the following fields were contacted and supplied data and opinions for the study:

1. Manned space flight
2. Deep space flight
3. Geosynchronous communications satellites
4. Military satellites and undersea electronic devices
5. Military missile nuclear war heads
6. Medical electronic implants
7. Commercial communications satellites
8. Commercial undersea telephone electronics

9. Commercial nuclear power instrumentation
10. Oil industry deep hole instrumentation

The current NASA documents related to STS flight hardware and Space Station Freedom hardware were reviewed. Various electronic engineering databases were searched using combinations of key words; e.g., prototyping, modelling, simulation, systems, hardware, etc. The "Computer Database Plus" yielded the following numbers of citations for the listed key words:

Key Words	No. of Citations
Prototyping or Modelling	66
Simulation and Hardware	28
Computer/Simulation/Prototype	4
Systems and Modelling	8
Systems and Simulation	295
Systems/Simulation/Hardware	16

These citations were all too general for direct utility to this study, except as statistical background. Good, vigorous analysis work pertaining to the effectiveness of prototyping in the engineering design process is scarce.

Algorithms and decision flow charts were synthesized which reflect the analysis of all of the data that were collected. These "road maps" simplify and organize the decision making process, but the raw data and opinions as summarized in the appendices of this report are the supporting documentation with additional details which cannot be adequately summarized in a few charts. The study utilized a consensus approach to gather and compile pragmatic data rather than approaches which are more inherently theoretical. The names and dates in parentheses that are contained throughout this report refer to the references of Appendices B and C.

It was found in the course of the study that a strictly numerical rating system would cause the user to lose sight of the overall system aspects. Thus, the use of more subjective inputs can retain the "common sense" reality of the output. For example, the political realities of the program cannot easily be quantified. Initially, it was assumed that the quantity and quality of prototypes required for any piece of hardware might be determined by some formula starting from "none." As the study progressed, it became obvious that

the interrelationships were too complex to model in a meaningful, yet simplistic, algorithm. Future studies of this type should consider the use of artificial intelligence (AI) techniques.

Thus, the methodology was revised to specify the ideal quantity and quality of prototypes required and then to identify the factors (or "drivers") which would cause an increase or decrease in the actual, required, prototyping activities. Attempts were made to separate engineering requirements from programmatic requirements; however, clear-cut distinctions could not always be made.

1.4 SCOPE

The development of Space Biology Initiative research hardware will involve intertwined hardware/software activities. Although the purpose of this study involved analyzing hardware, the software development impact must be considered and included in the analysis. Experience has shown that software development can be an expensive portion of a system design program. While software prototyping could imply the development of a significantly different end item, an operational system prototype must be considered to be a combination of software and hardware.

In the course of this study, hundreds of factors were identified that could be considered in determining the quantity and types of prototypes that should be constructed. In developing the decision models, these factors were combined and reduced by approximately ten-to-one in order to develop a manageable structure based on the major determining factors.

The Baseline SBI hardware list of Appendix D was examined and reviewed in detail; however, from the facts available it was impossible to identify the exact types and quantities of prototypes required for each of these items. Although the factors that must be considered could be enumerated for each of these pieces of equipment, the exact status and state of development of the equipment is variable and uncertain at this time.

2.0 FINDINGS

Examination of the SBI hardware development program and extensive discussions with experienced hardware developers both inside and outside NASA have disclosed a number of areas of concern common to all of the developers. The regularity with which the same problems surface in a variety of diverse programs indicates that they will recur during SBI hardware development. Solutions utilized by those interviewed are, in many cases, suitable for inclusion in this program from the beginning in order to preclude or minimize these predictable difficulties. The following sections discuss the identified problems relative to prototyping and their influence on hardware development. They also suggest solutions which are tailored to the SBI equipment development and procurement program. The findings of this study are presented as an assessment by consensus. Validation is also by consensus.

2.1 EQUIPMENT CATEGORIES

Previous programs have shown that SSF hardware systems will come from one of three sources: 1) Existing or modified flight rated hardware; 2) Adaptation of commercial off-the-shelf hardware; and 3) New design and development. Further, equipment will generally fall into one of two categories: 1) Experiment-unique, for scientific investigation; and 2) Operational, primarily for routine clinical tests, emergency usage, and some experiment support.

2.1.1 EXPERIMENT-UNIQUE EQUIPMENT

Equipment for experimental applications is intended to explore a particular phenomenon or group of objectives. Groups of standard operational equipment can be used, but customized special purpose equipment is more desirable in order to simplify configurations, increase probability of success, more efficiently use the crewperson's time, and increase precision.

With few exceptions, equipment in this class will be designed and developed specifically for its narrow field of investigaton. It is highly unlikely that any single piece of commercially available equipment can be adapted to perform the function, though several pieces of commercial hardware might be combined with new elements into a single, unique test system. Development of such a system, together

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with the other aspects of a research program, would normally be under the supervision of a scientist (Principal Investigator).

2.1.2 OPERATIONAL EQUIPMENT

This equipment is used, singly or in groups, for numerous applications which include vehicle/crew operations, health maintenance, emergencies, performance monitoring, or experiment support. It may be derived from modified flight or commercial off-the-shelf hardware or it may be custom designed. It will not normally be under the cognizance of a principal investigator but rather managed as a single item or group of instruments.

2.2 ADAPTATION OF COMMERCIAL OFF-THE-SHELF HARDWARE

In some cases commercial equipment exists which offers capability near that required for the space hardware. If a number of considerations related to the product and manufacturer are favorable, its adaptation can be a cost-effective and efficient method of obtaining the desired capability.

If executed or managed poorly, however, this approach can result in a very expensive, unreliable array of patches on top of patches. The preferred approach is to repackage as little as possible and to make fundamental mechanical or circuit redesigns only when absolutely necessary. If drastic changes are required, then the wrong unit has been selected for modification or a complete new design from "scratch" should be reconsidered. Since continuation of a modification program beyond a critical point leads so certainly to trouble, some mechanism should be built into the technical monitoring process which will trigger an automatic change to a new-design program. The inertia to continue such a program is tremendous. The management procedures should make it necessary to justify continuation rather than to justify a new start. The following cases, based on good and bad experiences, should be studied for their lessons in planning and implementing such a program.

Examples of very successful modifications are the Mini Oscilloscope (JOO1), which required a different power supply, and the Automatic Blood Pressure System (ABPS), which required repackaging. Both of these devices followed the rules of using highly qualified, modification-experienced, personnel and incorporating a minimum of

fundamental system changes. Unsuccessful adaptation efforts are numerous. The adverse experience in NASA and industry has been so costly in dollars or reputation that some of those involved have either moved on to other activities or refuse to discuss the problems unless the project names are not mentioned. (Buckley,1989; Evans,1989; Richards,1989)

2.2.1 MCOTS POTENTIAL CONTRIBUTION TO RELIABILITY

Proper use of commercial, off-the-shelf hardware can contribute significantly to the operational reliability of that SBI hardware which properly fits into a MCOTS program. Hardware that has been manufactured and distributed in quantity over several years has accumulated huge numbers of operational hours of experience. This database allows the manufacturer to reduce marginal designs and to factor component tolerances and selection into the product. This type of experience is usually lacking in hardware uniquely designed for space flight. The operational reliability demonstrated in the automotive and appliance industries, for example, has never really been achieved in equipment designed for limited distribution. This difference in experience occurs in spite of the fact that high-reliability components and rigorous design procedures are followed in some of those limited-distribution industries. Perhaps, each of the units that were manufactured and distributed commercially might be considered a prototype. Thus, the customers/consumers became the testers of numerous prototypes. This huge experience base of information is difficult to capture or duplicate by building a total of only four or five units.

This seemingly enigmatic experience can also be elicited from the various companies that attempted to make commercial products from medical hardware developed for the space program in the decade of the 1970s. In general, these companies found that commercial versions of the high-reliability equipment designed for space flight demonstrated disappointing operational reliability when manufactured and distributed in quantity. The existing "lower state-of-the-art" medical monitoring equipment that had been on the market for several years was significantly more reliable on an operational basis than the new-technology, high-reliability designs which had been proven extensively in theory and had even undergone full qualification testing. It was only when this hardware was produced in quantities over several years that it established an

operational reliability that was even of the same order of magnitude as the older commercial-off-the-shelf hardware.

Thus, one has to consider the subjective, informal prototype experience behind commercial-off-the-shelf equipment. A company that responds to its user's complaints and has mechanisms in place to change design, manufacturing ttechniques, procedures, and components based upon the ooperational experience of its customers can produce a superior product that is thoroughly "debugged." In evaluating commercial-off-the-shelf hardware, the huge numbers of "hidden prototypes" must not be forgotten or neglected. (Schulze, 1989)

2.2.2 MCOTS TECHNICAL SKILL REQUIREMENTS

The process of modifying commercial off-the-shelf equipment for use in a manned space program should be undertaken only by skilled engineers and technicians who have successfully performed this analysis and modification numerous times. There is a pronounced learning curve which is very demanding of newcomers to this activity. Well-developed engineering skills are required to determine the suitability of the existing system design, circuit implementation, component selection, interface compatibility, software design, etc. Related engineering experience is required to grasp fully the subtleties of a complex design, especially where the documentation is limited. Use of custom integrated circuits and sophisticated embedded computer functions add greatly to the skills required to identify the implications of modifying and applying a device in some way other than that intended by the original designer.

The use of COTS equipment generally requires careful assessment and evaluation of the following:

- Performance versus requirements
- Safety
- Capability to function in zero-g
- Materials compatibility (flammability, outgassing, shelf-life, etc.)
- Environmental qualification (vibration, shock, temperature, pressure, etc.)
- Weight and volume

In addition, special insight into the logic and procedures involved in FDA approval of medical equipment is needed to avoid invalidation of the extensive experience base inherent in commercially available medical products.

Practical experience and detailed knowledge of technical programmatic requirements is essential to assess the more mechanical attributes and limitations of a candidate for modification. The scope of experience required ranges across diverse technologies which include human factors, power sources, cooling, non-metallic materials, mechanical robustness, and potential impacts of extremes of thermal, shock, and vibration exposures.

Scientific and medical flight hardware will be used directly by the astronauts and should receive thorough human factors consideration. Hazards to the crew and demands on their time must be minimized. It is desirable for human factors experts to participate throughout the project. Personnel with extensive experience in training a variety of crew persons can be of immense benefit to the program. Continuous consideration of typical crew demands can prevent additional changes later in the program.

The variety and subtly of required skills approach those of an "art", implemented with extreme attention to detail. Miscalculation or under estimation can lead to a domino reaction of one change causing another--and then another. (Evans, 1989; Richards, 1989

2.2.3 MODIFICATION CANDIDATE SELECTION

Selection of a suitable candidate for a modification program requires much more than picking a good piece of hardware. Consideration must also be given to a series of other factors. These typically include the match between a product's performance and the required specifications, the factory's ability and interest in providing support, the extent of required modifications, the potential for repair/maintainability, and the total cost for modification, application, and lifetime support.

A selection process used successfully in the recent past by NASA for obtaining COTS medical and science related hardware incorporates the following steps:

1. Determine the useful performance features offered by each reasonable candidate unit available in the market.
2. Combine the most useful of these features into a composite-standard list of desired features.
3. Compare the capability of each candidate unit the optimum capability represented by the composite-standard list.

It is often useful to make a matrix which facilitates ranking the units numerically on each of the characteristics listed. This ranking, together with the evaluator's seasoned judgment, should provide a clear "best choice".

The single unit providing performance closest to the composite-standard becomes the prime candidate for selection. At this point, it is usually desirable to purchase the prime candidate and two or three close runners-up for further, detailed, examination.

Evaluation of each candidate should consider many factors, such as:

- Workmanship
- Robustness
- Internal element accessibility for repair/modification
- Human factors: location and feel of controls, displays, etc.
- Breakable glass or sharp edges
- Fundamental system engineering approach used
- Suitability of the circuit implementation
- Limits to fault propagation
- Test connectors or self diagnostic routines
- Quality, quantity, depth, and completeness of documentation for installation, operation and maintenance
- Software provided and availability of source codes and support
- Cooling technique and coldplate adaptability, if needed
- Power sources used and circuit overload protection
- Electrical, fluid, and gas interfaces
- Connector configuration
- Quantity and use or non-metallic materials
- Potential ignition sources, catalytic materials, etc.
- Hazardous materials - mercury, ethylene dioxide, etc.
- Nonstandard, unreliable, hazardous, or obsolete parts
- EMI emission or susceptibility
- Measured performance against advertised specifications
- Mechanical configuration: size, weight, shape, mounting, etc.
- Dependence on 1G for proper operation
- Electromechanical and data/computer interfaces

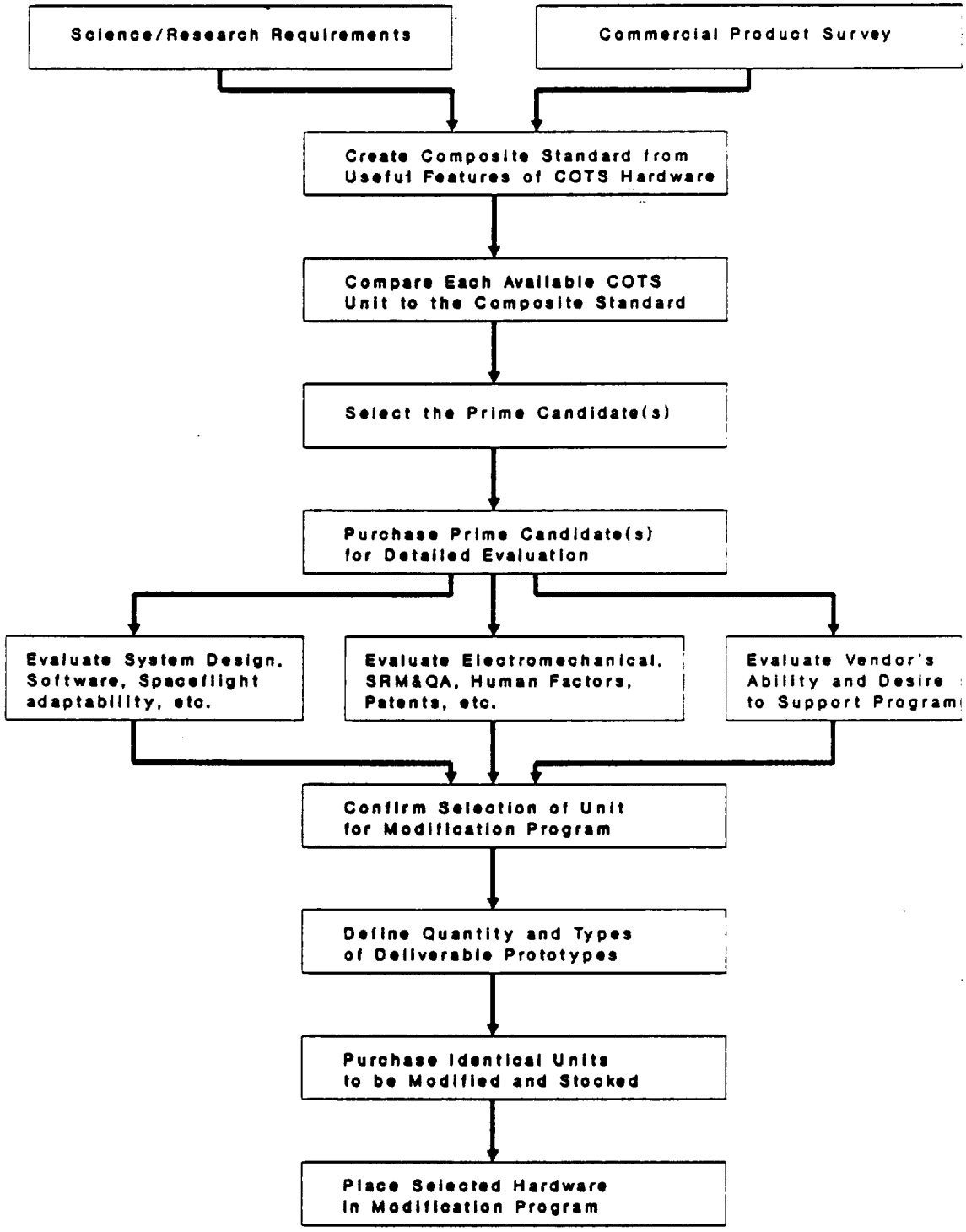
In addition to the detailed evaluation outlined above, discussions with the manufacturer and a visit to his factory should reveal his willingness and ability to support the product throughout the phases of modification and application. Chances of success increase with his degree of professionalism which is often reflected in the quality of his documentation. A lack of genuine interest and ability on his part should automatically disqualify the unit from further consideration. (Evans, 1989)

It is necessary to determine whether the essential documentation describing electrical, mechanical and software code designs is proprietary. The status of patent activity may make essential information unavailable or create disclosure limitations with which NASA cannot comply.

The proposed steps in a procedure for selecting and purchasing COTS hardware for modification are shown in the diagram of Figure 2.2-1.

Figure 2.2-1

Procedure for Selecting and Purchasing Commercial Off-The-Shelf Hardware for Modification



2.2.4 QUANTITY OF UNITS TO PURCHASE

The number of units required will normally include those for redesign, engineering test, interface compatibility test support, qualification testing, training, flight, and spares. Additional units should be purchased, and stored at this time, for cannibalization to provide unique parts and parts which will become obsolete and unavailable during the program life.

It is imperative that all units to be modified in a MCOTS program be identical before modification, both physically and electrically. Several actions may be taken in order to ensure that all units are the same. The units purchased should be from the middle of a single, stable, production run. They should have sequential serial numbers, unless one has been rejected for technical reasons. The total number of units ever to be purchased should be obtained at this time.

All documentation describing theory of circuit and mechanism operation, operation and repair procedures, software codes, and operational programming procedures should be obtained at the time of the purchase and should accurately describe any revisions or modifications incorporated in the product received. (Evans, 1989)

2.2.5 WHO SHOULD DO THE MODIFICATIONS?

It is very important for the modification team to possess expert ability in many areas. In-depth knowledge of the system, circuit, and software operation is essential. The original designer has an obvious advantage over any others in making design changes in these areas. It is, therefore, desirable for the designer to work with the NASA modification team if he or she is still employed by the manufacturer and if the manufacturer is cooperative.

Experience has shown, however, that manufacturers usually are not sufficiently familiar with many of the other requirements to be met for manned space flight. The experienced NASA modification team is in the best position to handle the engineering of other modifications beyond circuit and software changes.

Normally, a manufacturing facility is configured for production rather than for custom modification of hardware. While each situation must be judged separately, it might often be better to make the actual physical modifications in a NASA prototype shop or in a

private facility specializing in custom modification and fabrication. Organizations which develop specialized equipment for the military often have the necessary facilities, organization, and space-oriented knowledge.

The Shuttle teleprinter development is an example of a combined effort by a manufacturer and NASA. The apparatus was derived from a production millitary device. Honeywell pulled partially completed units from the production line, and made mechanical modifications in their model shops. NASA/JSC personnel designed and fabricated specialized interface electronics. NASA model shops fabricated a mechanical interface to a standard spacecraft locker. Qualification testing was performed in JSC facilities.

The teleprinter project demonstrates the cost and time-saving potential of modified off-the-shelf hardware. This six-month program (time from authorization to flight) provided the selection, design, modification, testing, qualification, and delivery to KSC. The equipment involved were electronic breadboards, a DVTU, a qualification model, four flight articles, GSE, a ground terminal and interface boxes. The cost was perhaps 25% of a new development from "scratch." The program success can be attributed to the excellent military product history and a highly motivated team with a full-time, dedicated manager who was personally challenged. (Evans, 1989; Richards, 1989)

2.3 NEW DESIGN AND DEVELOPMENT

2.3.1 GENERAL FINDINGS

The alternative to adaptation of existing hardware is the design and development of a completely new device or system. This approach, typical for experiment-unique equipment, allows the configuration and performance to be matched exactly to the task. It affords the opportunity to automate test set-up or configuration, calibration, operating procedures, data acquisition, calculations, and interpretation of results. Comparisons must be made to determine the extent of automation appropriate in each case.

In new designs, use may be made of common, interchangeable, functional modules. If these elements are to be compatible with other hardware systems, then it is imperative that a systems engineering approach be applied to all hardware involved. Special

care must be exercised in engineering, procurement, and technical management unless the common elements have been fully flight qualified before they are mandated for multiple usage.

Many tens of millions of dollars worth of GFE flight hardware has successfully been developed for manned space flight programs from Apollo through Shuttle using the following procedure as described by Sinderson (JSC,TCDD). The procedure is similar to that used for Life Sciences and other experimental and operational hardware.

A Representative Procurement, Qualification, and Maintenance Procedure

1. A document was generated which set down a preliminary set of requirements and interfaces.

2. A review was held including representatives of flight crew operations (users); project/program offices (funders); subsystem manager; supporting and interfacing groups such as hardware integration, payloads, and network communication (GSFC); reliability, safety, quality assurance, and integration/compatibility testing laboratories; and the engineering group designing and providing the hardware. Out of this review emerged a set of requirements which provided the best combination of capability, simplicity, cost effectiveness, SRM&QA, and potential for accommodating future needs. The resulting information was formalized in a document which became the basis for the subsequent engineering development, the specifications and the interface control document.

3. A buy-or-develop decision was made based on a thorough review of available hardware/techniques and in-house evaluations of candidate off-the-shelf devices.

4. If a suitable device was in production, the specification was adjusted and a MCOTS (modified commercial off-the-shelf) procurement program was initiated. Some modifications were accomplished within JSC while the manufacturer was willing and equipped to modify other products to accommodate special requirements such as selection or elimination of nonmetallic materials, reduction of weight, addition or elimination of some features, and incorporation of special testing.

5. If development was required, a program of in-house work was begun which included breadboarding critical elements, competitive evaluation of algorithms, system simulation, and extensive testing of candidate techniques in a fully integrated spacecraft and ground configuration. The in-house investigation and findings were completely documented and very detailed specifications and test criteria were prepared.

6. A competitive, often firm-fixed-price, procurement was initiated. Vendors were invited to propose implementations using the best and most cost-effective circuit and hardware techniques utilized in their facilities. The well-documented in-house NASA work eliminated vendors' concerns about potential expensive complications and produced a sufficiently high level of confidence to warrant minimum dollar, fixed-price proposals even where extensive development was involved.

7. The insight gained (and the definitive interface control documentation developed) during the in-house work provided an outstanding degree of integration compatibility of the delivered product.

8. Complete environmental test equipment was available in the JSC engineering laboratories, allowing qualification testing to be done either there or in the vendor's facility.

9. Complex maintenance and repair work was usually done at the vendor's facility. Spare parts and kits of parts for additional builds were maintained both in bonded storage at JSC and at the vendor's facility, since a limited number of units were produced and there was the possibility that critical components would become unavailable.

10. Hardware refurbishment and preparation for flight were accomplished at JSC while vehicle installation was done at KSC.

A highly successful variation of the above procedure involved a two-step approach. In the first phase, a contractor or in-house engineers researched the design prospects and built a proof of concept model which demonstrated the concept and its growth potential to management for programmatic approval. The second phase incorporated a separate hardware development program as described in steps 1-10 above. A highly successful example of such a

two-phase program was the LCRU (Lunar Communication Relay Unit) which sent live television directly from the Moon to Earth under the real time command of an operator in the JSC Mission Control Center.

The following sections provide additional information related to the procedural steps above. The information is derived from a consensus of the individuals providing the experience data base.

2.3.2 REQUIREMENT DEVELOPMENT

There apparently exists some disagreement over the semantics of a requirement versus a specification. A reasonable understanding can be obtained by considering a "spectrum" of specificity. One end can be defined as a requirement and the other end as a specification. Although they deal with the same essential elements, they vary in degree of specificity. For the purposes of flight hardware development, it is appropriate to define a requirement as a broad statement of the need, one which describes the capability or the functions to be provided and the circumstances under which they will operate.

Conversely, a specification describes precisely the capability, the method of providing it, the exact details of the environment and resources, as well as the test methods and acceptable limits by which the performance will be confirmed.

A special challenge exists in the clarification of requirements in science and medical-related hardware development. There is a perception that many scientists and engineers view requirements, specifications, and developments so differently that there exists a fundamental communications problem. Deliberate action must be taken to bring the scientists (who have the need) and the engineers (who will fulfill it) together in a cooperative relationship which will foster creativity, productivity, and quality. Though the personnel may report to different organizations, it should be possible to create a spirit which bonds them as a team, stimulating communication while defining responsibilities and expectations. The result can be a synergism of creativity and energy which allows sharing successes as well as failures. The team, probably best moderated by a senior engineering manager, should scrub the requirements until clear statements exist which properly describe the need without "gold plating." (Evans, 1989; Sinderson, 1989)

2.3.3 TECHNIQUE AND APPROACH RESEARCH

With a clear statement of the requirements in hand, the team can methodically explore for the best theoretical and practical methods for solution of the basic problem. This may well include laboratory evaluation of various techniques, algorithms, etc.

A survey of the market place can reveal which of the theoretical methods are being used commercially. Examination of the equipment in use in the field will reveal the ease of application, reliability, accuracy as well as subtle problems in the man/machine interface.

A 'Phase A" study by specialized experts in the field has been productive in many instances. The refinement of in-house expertise which occurs in this process is invaluable in implementing the actual hardware development.

A well-defined approach, which utilizes the in-house information, perhaps augmented by experience with laboratory hardware, can be formulated. Good documentation from this work serves to inform management of technical details, to help secure funding, and to dispel apprehensions of potential bidders concerning the difficulties and unknowns in building the article. Experience has shown that the technique can sufficiently satisfy bidders to result in firm-fixed-price contracts, an excellent control of costs.

2.3.4 SPECIFICATION DEVELOPMENT

The ground work described above results in the insight and detailed information needed to generate a thorough, detailed, specification. Few things have more value in cost effectively obtaining excellent prototype hardware than a good specification. A major cost-cutting aspect of a well-developed specification is its ability to avoid technical changes and disputes over test methods and tolerances.

2.3.5 TECHNICAL MONITORING

The technical monitor should be a prime member of the NASA engineering team. He is the only person other than the procurement officer who can give direction to the contractor. All of his direction must be of a technical nature and must be within the scope of the contract. Changes of scope alter the contract's dollar value and must be negotiated by the contracting officer only.

The development of some medical experiment hardware for Skylab used a manufacturer's expertise to substitute for the Phase A and team activity described above. In these cases, the PI acted as the technical monitor. Breadboards were moved from the contractor's to JSC's laboratories where testing with human subject was done. A high degree of cooperation was achieved and high-quality equipment resulted. The need for JSC in-house work is greater now because there are very few appropriate manufacturers remaining with both medical and space flight hardware experience. NASA must take the technical lead in cultivating an industry support base.

2.3.6 ANALYSIS AND REVIEW

In addition to the pre-procurement analyses discussed above, many other areas of design analyses exist which may potentially add to the assurance that the prototype and flight system will be safe and reliable. The following list identifies many elemental analyses from the conceptual, preliminary, and final design phases. The size, criticality, sophistication, and specific end product of a development program determine which items are appropriate.

1 Conceptual design phase
   a. Preliminary hazards analysis
   b. Preliminary failure modes and effects analysis (FMEA)
   c. Reliability allocations
   d. Conceptual design review
2. Preliminary design phase
   a. Preliminary hazards analysis (update)
   b. Preliminary FMEA (update)
   c. Reliability allocation (update)
   d. Common cause failure analysis
   e. Redundancy techniques/standby
   f. Preliminary fault tree analysis (FTA)
   g. Stress/strength analysis
   h. Configuration optimization technique
   i. System design review (PDR)
3. Final design phase
   a. Hazards analysis
   b. FMEA
   c. Reliability predictions
   d. Breadboard, brassboard, mockup, & engineering modes tests
   e. Critical design review (CDR)

f. Qualification tests
g. Equipment design reviews
   - Changes
   - Data requirements

4. Post-Production phase
   a. Verification
   b. Certification
   c. Flight Readiness Review (FRR)

Obviously, guidance by an experienced technical monitor is essential to keep most manufacturers out of bureaucratic trouble. The need for some programmatic requirement simplification to achieve affordable reliability is addressed later in this report.

2.3.7 TEST AND EVALUATION OF ENGINEERING MODEL

This unit, similar to the flight unit except for its construction with commercial parts, is perhaps the most important of all prototypes. It receives all changes and every type of test, usually to levels exceeding flight and qualification. As a result, there should be no need to make any changes whatever to the qualification or flight units. There is more known about this unit than any other--ever. By subjecting it to higher than the qualification level in every test, it is possible to define the margins of physical and electrical performance for the flight articles. The engineering documentation developed on this unit should be complete. Under normal circumstances, the extremely rigorous SRM&QA documentation begins after this unit. With all problems solved using the engineering model, it should be possible for the qualification and flight units to move on through assembly and test without any negative documentation.

2.3.8 FABRICATION OF TRAINING AND QUALIFICATION UNITS

The training unit is normally the last of the units to be built under prototype conditions and controls. It should be configured and operated very much like the flight articles. The primary difference is that it is normally built with commercial quality parts. In some instances, there is a desire for it to serve as a flight spare. If that is the plan, it must be built identically to flight units and under the same controls and documentation. This arrangement can be undesirable since its primary training use would be very restricted and encumbered by operating limitations, required presence of

inspectors, and documentation. The original objective, to reduce costs, could easily be lost in the "red tape."

The qualification unit is usually the first item off the flight article assembly line. This is desirable since it truly represents the flight article. However, if it does not pass qualification tests, the flight articles built along with it must receive the same modifications that it receives.

2.3.9 FLIGHT HARDWARE PRODUCTION

"Production", when used to describe flight hardware is perhaps a misnomer since there are so few units built. It does imply the correct impression that such units are the highest quality and best documented units available. Full SRM&QA (suitable for the criticality class) imposed.

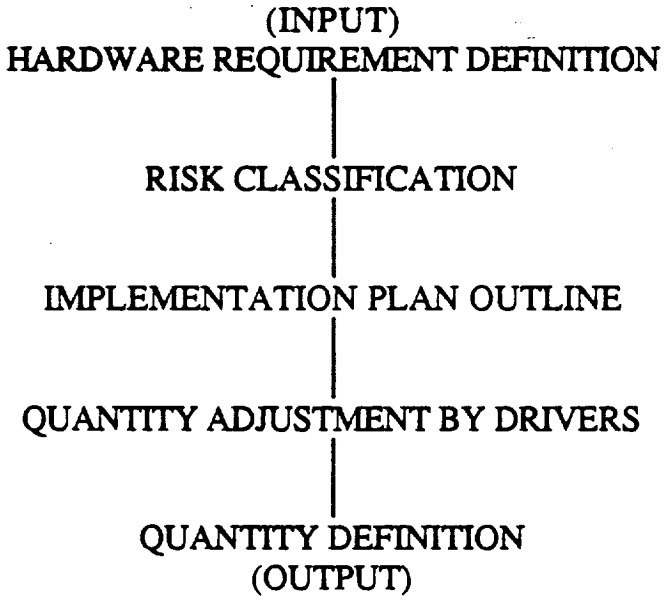
2.3.10 SPARES, REPAIR AND MAINTENANCE PROGRAM

Information gained in the prototype analysis and testing program adds to the original criticality definition to confirm the planning basis for this activity. The specifics of the spare parts inventory are driven by the design and flight application. Detailed drawings, schematics, software source/debug codes, adjustment/allingment procedures and perhaps an "expert system" for trouble-shooting and repair are all forms of documentation which must be obtained at the time of design and fabrication. Shuttle experience has shown that economy here is very short-sighted. If it is possible at all, later reconstruction of this information is extemely expensive. (Sinderson, 1989; Richards, 1989)

2.4 DETERMINATION OF PROTOTYPE/FLIGHT QUANTITIES

2.4.1 CONCEPT OF DETERMINATION METHOD

The many factors which influence the required number of prototypes have been combined and arranged into a logic flow with three fundamental steps. The logic moves from an input of hardware requirement definition, through 1) risk classification, 2) implementation plan outline, and 3) quantity adjustment, to emerge as the quantity definition output, as shown below.



2.4.2 DEFINITION OF REQUIRED TERMS

A clear understanding of the quantity definition method requires that several terms be understood. They are:

PAYLOAD CLASSES:

- Class A payloads are those for which a minimum risk approach is clearly dictated by prohibitively high cost of consequence of failure, or by unacceptable combination of costs and intangible factors associated with failure. A full formal qualification and acceptance program is mandatory.

- Class B payloads are those for which an approach characterized by reasonable compromise between minimum risks and minimum costs is appropriate due to the

capability to recover from in-flight failure by some means that is marginally acceptable. The qualification and acceptance program is less stringent than Class A.

- Class C payloads are those for which re-flight is a possibility. This class was originally established for certain STS payloads where manifesting can accommodate a re-flight in the event of an in-flight payload associated failure. Duration of payload operations for Space Station can be orders of magnitude greater than on STS, and the policies concerning routine re-flight on Space Station have not yet been established. On-orbit servicing may enable recovery from failure without the requirement for a separate flight opportunity. The qualification and acceptance program is less formalized than in Class B.

- Class D payloads are those that have objectives worth achieving at a cost not to exceed the amount required for a single, low-cost attempt. The qualification and acceptance program is limited to verifying safety and interface compatibility.

(From OSSA Classification Instruction, 1988)

PROTOTYPE UTILIZATION:

- Conventional Development: A development program using a sequence of progressively more complex prototype units for each step from concept through engineering development and on to qualification testing.

- Protoflight Development: A procedure in which only one flight model (PFM) is built to flight standards with high-reliability parts. Some use this unit for development, qualification testing, and flight, ESA and others include an engineering moder (EM).

EQUIPMENT SOURCES:

- Modified Commercial Off-The-Shelf (MCOTS): Equipment in commercial production which, with modification, can be adapted for flight.

- New Development: A development program starting from a "clean page", using either a conventional development or protoflight program, as appropriate.

2.4.3 OUTLINE OF PLANS

One of two development and prototype utilization plans is used. The plan selected depends on the class of the equipment (A and B or C and D). Each plan is designed around a different "reference" quantity of prototype equipment and a different degree of SR&QA rigor. Each plan is outlined below:

PLAN #1, a minimum cost approach for classes A & B:

- The number of units shown is the reference quantity and will be modified by the drivers. It is based on consensus.
- Analysis, reviews, SR&QA, and testing are rigorous.
- Engineering development is based on MCOTS or a new start.
- Use this reference quantity to support these functions:

Number of Units	Function Supported
1 - Brassboard	•Hardware and software design
1 - Engineering unit	•Design adjustments and tests •System interface compatibility tests •Software performance tests •Testing - through qualification level •All changes and fixes •Mechanical interface tests •EMI tests •Human factors integration •Confirmation of flight harness
1 - Qualification unit	•Qualification tests •Training
1 - Flight unit	•Flight (application may require more)
1 - Spare	•Flight

- Repair and Maintenance Program (Quantity depends upon whether equipment is built from new-start or is MCOTS)
  - If MCOTS . . . . . Add 3 more units during purchase for cannibalization and/or for additional build.
  - If New Start . . . . . .Buy parts for 2 complete kits plus buy selected critical parts. (a kit is all the parts, except chassis, required to build on unit)

PLAN #2, a minimum cost approach for classes C & D

- The number of units shown is the reference quantity and will by modified by the drivers. It is based on consensus.
- Analysis, reviews, SR&QA, and testing are less rigorous.
- Engineering development is based on MCOTS or a new start.
- Use this reference quantity to support these functions:

Number of Units	Function Supported
0 - Brassboard	•Use computer simulation to substitute for soft/hardware testing.
1 - Engineering unit	•Design adjustments and test •System interface compatibilty tests •Software performance tests •Testing - through qualification level •All changes and fixes •Mechanical interface tests •EMI tests •Human factors integration •Training (change from plan #1)
1 - Protoflight unit	•Qualification tests •Flight
0 - Spare	
0 - Training	

- Repair and Maintenance Program (Quantity depends upon whether equipment is built from new-start or is MCOTS)

  If MCOTS: Add 2 more units during purchase for cannibalization and /or for additional build.

  If New Start: Buy parts for one complete kit plus buy selected critical parts. (kit is all the parts, except for chassis, required to build one unit.)

2.4.4 QUANTITY DRIVERS

A large number of additional factors which influence the quantity of prototype units have been combined and grouped into the items on the following list. The reference quantities in each of the two plans should be adjusted down or up in response to the applicability of these factors for each design project.

PROTOTYPE QUANTITY DRIVERS

IMPACT OF FAILURE

This factor allows adjustment for extremes of safety, unusually expensive interfacing apparatus, critical timing of coordinated events, excessive media coverage, etc.

TECHNOLOGY MATURITY

If, for example, the apparatus has been derived from a high-quality commercial model which has been in broad use for a number of years, a brassboard might not be needed and less time might be spent refining the computer codes. On the other hand, a first-time application of a state-of-the-art technique will require the full complement of prototypes.

INTERFACE COMPLEXITY

Additional engineering models might be required for independent, simultaneous tests for a device with numerous complex interfaces.

DEGREE OF PROTOTYPE REUSE

In some cases, it is possible to use prototype hardware for more than a single purpose. For example, it might be possible to utilize the engineering model as a training unit for an application where the program timing, regulations, and simplicity are favorable. (See Figure 2.4-2)

FLIGHT USE AND DURATION

Requirements for multiple simultaneous uses of a device will obbiously require more flight articles as will very long-duration critical applications where sparing is a factor.

APPLICATION LEAD TIME

Additional prototype articles can be required when the development program is very short. Simultaneous engineering development of hardware and software, multiple interface tests, and training at multiple sites can readily increase the prototype and TU requirements.

2.4.5 QUANTITY SELECTION PROCEDURE

Figure 2.4-1 brings together graphically all of the sub-elements which have been explained in the previous sections. A hardware class determination is made from the hardware requirements and the flow chart is entered from the left. Classes A and B are implemented by Plan #1 which delineates a set of prototypes to start with. On the right, the quantity drivers are applied, altering quantities down or up as described.
In similar manner, classes C and D utilize Plan #2. The drivers are applied to the plan's standard quantity to derive the numbers to be built. Since there is only one flight article, it is impossible to reduce that element further.

2.4.6 PROTOTYPE USAGE MATRIX

Figure 2.4-2 identifies various ways in which multiple use can be made of prototype hardware. In some cases special permission must be obtained to use the units as indicated. Special precautions are needed to safeguard the equipment and to document its various exposures.

Figure 2.4-1

Procedure for Selecting Development/Procurement Plan

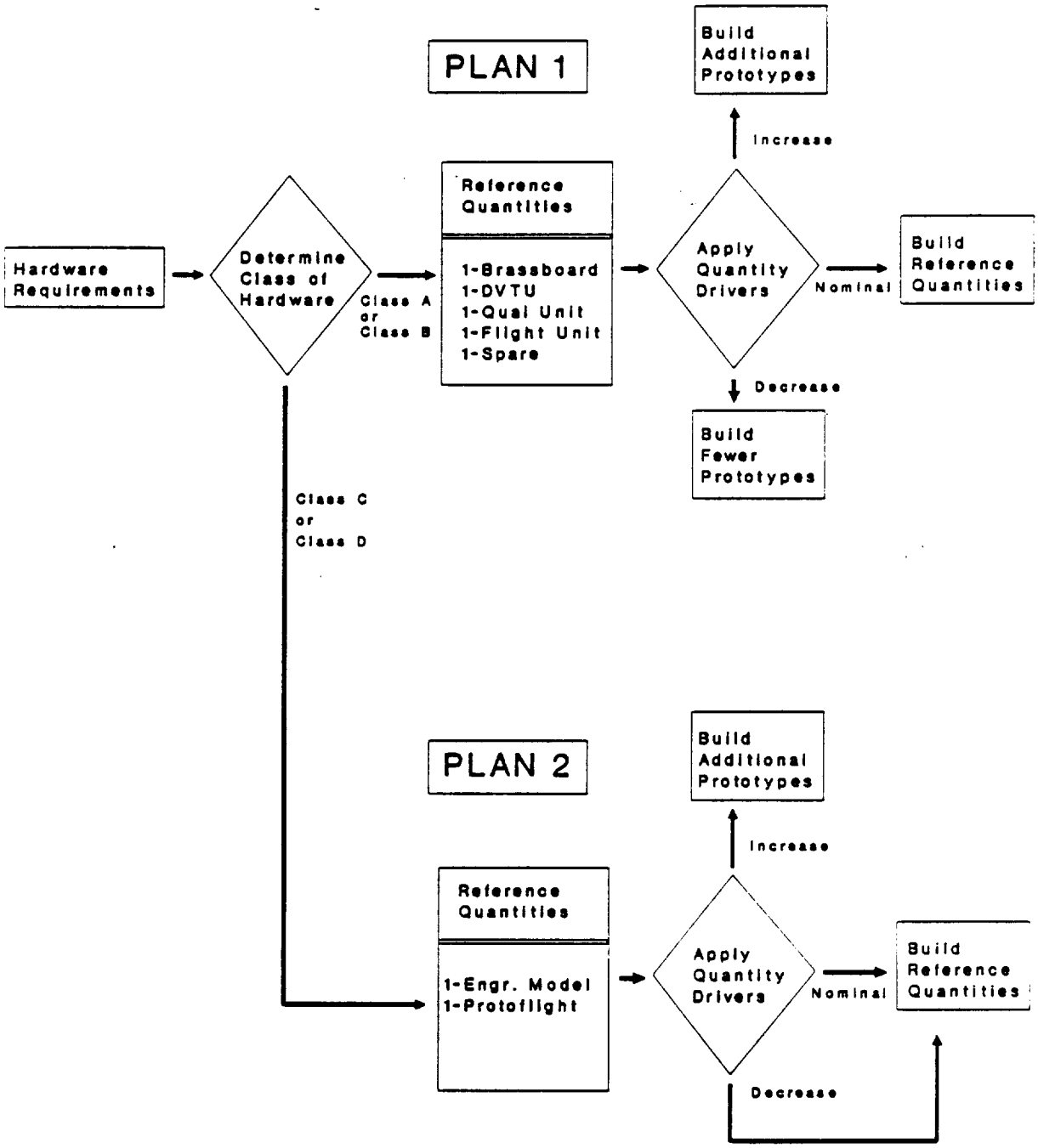


Figure 2.4-2

SUMMARY OF MULTIPLE USAGE OF HARDWARE

HARDWARE UNIT	APPLICATION					
	Devel-opment	Engr. Tests	Qual. Test	Spare	Training	Flight
Breadboard	X	X				
Brassboard	X	X				
Engineering Model	X	X			X	
Qual. Unit			X	(X)	(X)	(X)
Training Unit				(X)	X	
Flight Unit(s)						X
Back-Up Unit(s)				X	(X)	X

( ) Denotes special procedures and controls required.

Decisions regarding multiple uses are usually programmatic decisions which cannot be completely defined by technical factors. The cost savings in prototype deliverables is obvious if multiple uses can be made a part of the program plan.

2.5 RELATIVE COSTS

The relative costs (see Figure 2.5-1) of prototyping are dependent upon numerous and diverse factors. The major ractors impacting the incremental cost of the hardware development program are associated with the fidelity of the construction and the requirements for deliverabililty. The cost is influenced by such subtle factors as the accounting system used by the subcontractor; i.e., "Is engineering overhead or manufacturing overhead applied to the construction effort?" The expense to prepare and deliver prototypes on an expedited schedule can add to the cost of the program. If the prototype can be retained at the vendor's plant or if it can be built and delivered with other hardware, some cost savings can result from seemingly minor programmatic changes.

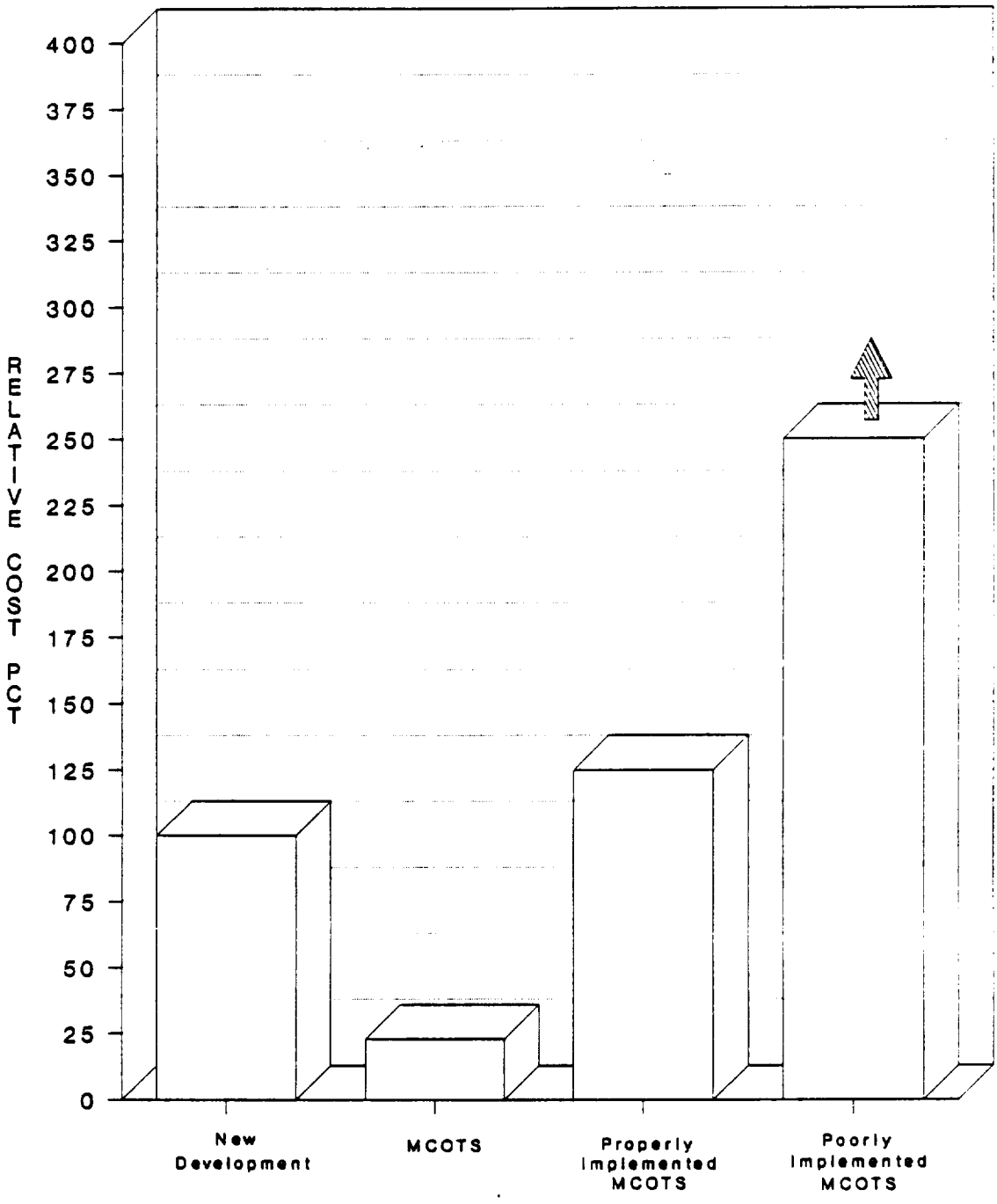
2.5.1 AFFECT OF PROTOTYPES ON PROGRAM COSTS

It is clear that each higher level of prototype is usually progressively more expensive. However, the managers of a number of programs have discovered (after the fact) that reducing the number of prototypes in a program does not necessarily reduce the program cost. In fact, there are numerous instances where the shortage of an engineering model has significantly increased the cost of R&QA documentation and manpower. Lost time in the engineering, environmental testing, and training areas can easily occur when equipment in not available when needed. A shortage of units for testing complex interfaces can easily cause testing delays in concurrent and adjacent projects where interface testing is scheduled.

The actual cost of <u>all</u> prototype hardware is very low when compared to the cost of the development program and the flight hardware. Numerous economies of construction are and can be practiced in the construction of prototypes, such as the use of commercial grade parts rather than expensive, high-reliability items. Breadboards and brassboards are also usually built without special enclosures and expensive connectors. The increased reliability associated with design maturity and the efficient utilization of design and test time

Figure 2.5-1

RELATIVE COSTS of DEVELOPMENT



made possible through assembly of adequate prototypes represent value to the program that can far exceed the cost of increased prototyping activity over the minimal amount required to deliver hardware.

If the technology is well-defined and a detailed end item specification can be written, then it is frequently possible to obtain a firm-fixed-price contract. In such a contract, there is normally no additional cost for some prototypes (such as breadboards), since these prototypes are an essential, inherent part of the design and development process. Thus, the cost of a breadboard does not necessarily represent and incremental cost to the program. This should be noted and accommodated by any cost models that use number of prototypes as an input.

2.5.2 COST OF MCOTS PROGRAM VERSUS NEW DEVELOPMENT

The relative costs of developoing equipment in a well-conducted MCOTS program may be kept to a total of about 15 to 25 percent of the cost of a full new development. It is possible that problems beyond the control of the engineering team will occur at some point during the program. If the MCOTS program is halted in a timely manner and a new development is efficiently initiated, the costs can be kept in the order of 125 percent of what a new development would have cost in the beginning. On the other hand, costs can ren several hundred percent of a new development if an MCOTS development is carried on for a long time beyond the optimum break point. These realtive costs are shown graphically in Figure 2.5-1. (Buckley, 1989; Evans, 1989, Land, 1989)

2.6 PARTS CONSIDERATIONS

Various component part problems in the U.S. have a major impact on the development of a prototyping strategy. They impact commercial, industrial, military, and NASA activities in many similar ways. Because of their complexity, the problems will be subdivided into those affecting high and then moderate reliability applications.

2.6.1 IDENTIFYING THE PROBLEMS

Maximum reliability applications: Criticality 1 and Class A applications demand that everything possible be done to ensure reliable operation. When the SBI equipment is deployed in

conjunction with the Space Station Freedom, the problem is compounded by the extremely long operational life requirements. Clearly the best parts obtainable are required for this application. Three major factors impact the availablilty of the desired parts.

First, the electronic component industry in the United States appears to be deteriorating rapidly. Many part manufacturers have ceased manufacturing operations in the U.S. Others have been sold to foreign interests and still others have moved off-shore. There exists no U.S.-made source for many types of parts and for others there is no second source. Many uncertainties and unacceptable delays reduce the utility of foreign sources.

Second, the technology associated with many parts, especially integrated circuits, is changing very rapidly. New, improved products, are brought on-line continuously at a rapid rate. The older products are quickly dropped from inventory, as is the support for obsolete items. Typically, a new computer processor or memory chip now becomes obsolete in two to three years and support is dropped in another two. Some parts experts have observed that by the time an "S" part has been approved for NASA's qualified parts lists it is perhaps half way to obsolescnece and it will have been superseded by flight time. Many Shuttle systems contain parts which are obsolete and totally unavailable. Redesign is usually the only viable recourse. Electronics for the RMS arm, the main computers, the radar, and data recorders are but a few systems being redesigned at this time.

Third, NASA's quantity requirement is generally too small either to interest manufacturers in extending component availability or to warrant the expense of dedicated custom fabrication facilities. The high cost of qualifying a part for "S" rating, for example, tends to cause manufacturers to stretch availability.

Moderate reliability applications: The problems affecting high-reliability parts apply equally to moderate-reliability applications as well. Some consolation in this area can be derived from noting that the quality of military and commercial microcircuits and certain other components has increased markedly. The large production quantities of some of these parts tends to keep them on the market a little longer. The extremely long operational life required for use on SSF introduces many problems with availability of repair components, even for moderate reliability applications.

2.6.2 CANDIDATE SOLUTIONS

Although there are few good solutions to these problems, several candidate solutions are listed below:

Maximum reliability applications: Many experts consider the following actions to be appropriate in an effort to achieve maximum reliability. Some of these are not exactly component solutions but are strategically associated with the desired objective.

- Use components and circuit designs which have a maximum
- of maturity or heritage, but which are not approaching end of useful life
- Use the highest grade of parts available (S)
- Use highly integrated devices in order to minimize the parts count and the amount of circuitry outside the device packages
- Configure all custom designed circuitry to facilitate computer testing
- Use extensive assembly and fabrication controls
- Refine the design by the proper use of prototypes and design reviews
- Utilize adequate engineering models
- Use extreme caution in 100% incoming component test to avoid subtle damage to components due to static charge, humidity in temperature cycle, contamination of leads by chemical contact with skin, etc.
- Store spares in an inert environment
- Avoid devices which are not hermetically sealed
- Consider possible radiation hardening for high density memories in applications subject to SEU ("single event upset" associated with high energy particles in space)
- Always include a mild random shake test with tests imposed on 100% of flight articles
- Analyze performance signature during test
- Stockpile spares
- Monitor spares
- Consider component DPA (Destructive Physical Analysis - discussed below) with batch signature

Destructive Physical Analysis is the name given to a process which provides a complex signature for sectioned samples taken from a component production line. It detects subtle changes in the product

generation process before more catastrophic problems develop. Allied-Signal Aerospace Company is one group who performs this test in conjunction with the Naval Weapons Support Center, Crane, Indiana. It is applied to components in various nuclear warheads and a broad variety of electronic devices and weapon systems.

The process allows detection of any change (induced by manufacturing variations) which has occurred in a device and which would cause it to be different in any way from the original qualification devices. "We have found this expecially useful with semiconductor products where the generating processes are complex and interrelated and initial changes in output performance are not readily detectable by other means. Once a semiconductor lot is qualified, destructive physical analysis samples are taken from all succeeding lots, which not only help detect subtle changes in the process, but also show lot-to-lot variations which make more visible the degree of vendor process control." (Wilson, 1989)

It is possible that the use of this or a related process could substitute for some of the testing and inspection involved in producing "S" level parts. The outcome might conceivably be equally reliable, but less expensive components, with much shorter delivery times. Information on the process is being provided to NASA/JSC and SR&QA for consideration.

Moderate reliability applications: The major reliability problems of custom-designed hardware, typical of that used in the space programs, are workmanship and design imperfections. In mass-produced products, where these problems have been gradually refined out, the problem of component part reliability becomes more obvious. Space hardware never has enough total operating time, with enough operational feedback, to reach this state. Therefore, while the reliabililty of components is important, the design and manufacturing techniques must be given an unusual amount of attention. These observations make it clear that commercial and military components are suitable for a great many SSF applications. The items listed below should receive attention when developing SSF flight hardware of moderate reliability:

- Achieve design maturity through use of proven circuits, devices, algorithms, and software together with extensive engineering testing.
- Use an adequate number of engineering prototypes

- Use proven fabrication techniques and controls
- Use burned and tested Mil-spec. parts
- Stockpile kits of components for repairs or additional builds (store in inert environment)
- If item is MCOTS, stockpile parts and unmodified units for cannibalization in an inert environment
- Provide a liberal quantity of flight spares
- Consider a shorter replacement life cycle

In view of the complex part situation, it is anticipated that repair will become a serious limitation to the long service life of each item. It is suggested that consideration be given to a shorter replacement life cycle of perhaps five years or less. Such a period seems more consistent with the present and expected component obsolescence cycle time. This possibility should be given much more detailed study by qualified experts, since its impact on design and parts selection in prototype and flight hardware is very significant. (Goeke, Holt, Hymer, Ramsey, Wilson, all 1989)

2.7 PROGRAMMATIC REQUIREMENTS

The Space Station Freedom is a very complicated project and there must necessarily be a great many rules and regulations which must be strictly followed. These rules, which are referred to here as programmatic requirements, are contained in hundreds of documents containing tens of thousands of pages of details.

The details which apply to the development of prototype and flight hardware are distributed throughout a large percentage of the documents. Many of the rules have not been completed and contain numerous TBDs. It is not yet possible to define absolutely which of the incomplete rules apply to prototyping. There is no known document which summarized which requirements the designers of equipment such as SBI hardware must meet. By comparison, the STS program has succeeded in compiling such summaries, though the one applying to DTO/DSO was signed as late as March, 1989.

A major impact on the SBI of not having summary requirements documents is high cost. Every designer/vendor must adhere strictly to these requirements. In order to do so, each must possess an immense set of ever-changing documents and have an operating understanding of which rules he must follow. At the beginning of a contract, a binding legal document defines his regulatory obligation.

This situation is generally like that in any Government contract, except it is unusually extensive and continually changing. It is necessary that planners and designers recognize the cost impact of the technical and legal staff each contractor must access. Completion of the TBDs and some simplifying and summarizing documentation is necessary before cost effective SBI prototype development can begin.

The designer's problem can be better appreciated by a review of Appendix A which is a partial list of applicable documents. Many are still incomplete and others will be added to the list as they are defined. A file drawer of these documents as they now exist can be intimidating to a small vendor of SBI hardware.

3.0 RECOMMENDATIONS

The following recommendations are based on extensive inputs from industry and NASA's Life Sciences and Engineering personnel. The recommendations might be applied essentially to most of the laboratory equipment which will be flown and operated on the Space Station Freedom. They apply directly to the SBI equipment and in particular to the cost-effective use of prototypes in development of that equipment. Their desired impact is to: 1) keep costs down, 2) provide the necessary degree of reliability, 3) provide the functional capability required, and 4) ensure that the vendors are able and willing to participate in the associated development and production programs.

1. Use a systems engineering approach to integrate and coordinage development programs for SBI devices which are expected to share common hardware element designs. It is essential that the designs incorporate the common requirements. Further, the development of common elements must be complete and qualified/verified prior to imposing their use on other system designs. Failure of a mandated common element design could cause failure of other systems in which it was used.

2. Automate functions requiring higher levels of operator knowledge. Education and skill training can be cost beneficial in many systems. Incorporation of automation in any SBI hardware development program may have an impact on prototype quantities and utilization and should, therefore, be considered in the very earliest stages of planning and development.

3. Establish shorter use/life expectations for SBI hardware. By initiating a replacement development program at the four-to-five year point, costly problems may be avoided. Such problems include hardware/software obsolescence, loss of developer engineering support capability, loss of component manufacturing sources, increased failure rate of hardware approaching the end of its useful life, and the expense of stocking and tracking critical and obsolete parts.

4. Stress risk-reduction, not low initial costs alone, in the development of hardware for long-duration applications on Space Station Freedom.

5. Incorporate ways productively to combine science and engineering personnel in teams for generation of detailed flight hardware requirements and specifications and for management of the development programs. These diverse talents, frequently located in different organizations, must fully cooperate to evolve efficiently the necessary hardware capability.

6. Re-establish long-term, in-house expertise in flight equipment engineering, modification, application, and support. It has been repeatedly shown that strong in-house capability is essential in obtaining good reliable flight equipment at the lowest possible cost.

7. Generate integrated technical requirements documents. Although excellent work has been done in the generation of the technical requirement documents which define SSF hardware development and its application, there are many TBDs remaining which must be clarified before SBI flight hardware contractors can begin their work. Serious consideration needs to be given to methods of simplifying the designers' task of properly applying these directives. Most manufacturers would be forced to incorporate a large staff, over a considerable period of time, to insure adherence to the thousands of applicable details. The cost for such a staff, (which must be added onto the actual hardware expense) would be significant. Small manufacturers, who comprehend the magnitude and seriousness of the problem, simply might not be able to bid on SBI development work for lack of staff experienced in reading and interpreting large stacks of specifications.

8. Examine the actual long-term reliability improvement due to the use of "S" level parts. Many factors in the U.S. component manufacturing industry have changed. Today's very rapid rate of electronic component obsolescence and the short period of availability (with technical support) demand careful attention to the effects on hardware development cycles, repair/maintenance, and logistics. Use of other MIL-specification levels, batch sample signature techniques, and more frequent redesign cycles are some factors which should be examined for potential solutions to long component procurement lead times and high program-life costs.

9. Develop mechanisms for indemnifying hardware and software development contractors. Rapid changes in U.S. litigation practices have made it almost impossible for small-to-medium-sized manufacturers of medical equipment to obtain reasonably priced

product liability insurance. Quoted insurance premiums may run several orders of magnitude more than the hardware costs. Large companies with an existing insurance "umbrella," covering many product lines, are able to obtain coverage at high, but manageable, costs. However, in many instances small specialized manufacturers are needed for their level of expertise, experience with development hardware, and their more acute interest in production of small quantities of customized prototype and flight hardware.

10. Standardize batteries and chargers. A recurring problem, obvious from a review of the SBI hardware list and common to adaptation of off-the-shelf hardware, is associated with the power source. Modern electronic hardware is frequently designed to utilize rechargeable batteries. More convenient and cost-effective use can be made of commercial off-the-shelf hardware if NASA can determine safe and acceptable methods which allow less restrictive use of rechargeable batteries. Utilizing conventional power sources can reduce the tests required in order to prove the performance of the power supply interfaces.

4.0 CONCLUSIONS

Prototype hardware development programs conducted by NASA and within various industries offer an experience knowledge-base which is very useful in establishing guidelines and procedures to be used by planners and developers providing future space biology research hardware. This study has been able to combine such knowledge with contemporary facts related to SSF regulations and component limitations to evolve information which should contribute to the success and cost efficiency of SBI hardware development. The following items summarize the major findings of this study for ease of application:

1. Prototype development programs may be subdivided according to: 1) type of application, 2) degree of reliability required (class), 3) availability of usable devices in the commercial market, and 4) the required useful life expectancy.

2. The numbers of required units and the development implementation methods may be determined using an algorithm described in Figure 2.4-1 and the associated text (Section 2.4) together with consideration of sets of "drivers."

3. There are two principal approaches to SBI hardware development that drive prototype development programs: 1) modification of commercial off-the-shelf equipment and 2) new development.

4. Each approach can be generalized with essential steps and hazards as identified in Sections 2.2 and 2.3.

5. Prototypes are needed to varying degrees in hardware and software development programs of every type.

6. Computer simulation can substitute, in some cases, for breadboard and brassboard prototypes.

7. Nothing can efficiently substitute for the design verification test unit (DVTU) or engineering model (EM) prototype.

8. The operational experience base of an MCOTS prototype program can enhance reliability due to product maturity and evolution from extensive user feedback.

9. Significant engineering design efforts and extensive prototype testing must be accomplished in a new-build development program in order to approach the maturity of an MCOTS development.

10. A MCOTS prototype development program can potentially provide a good flight article for a cost of 15 to 25% of a full new development program. If done poorly it can cost many times as much as a new development.

11. It is necessary to build a mechanism into an MCOTS program which will terminate the program and activiate a new build from "scratch" if problems exceed certain limits.

12. The actual cost of a full complement of prototype development hardware is very small compared to the development itself and the associated flight hardware. It is small also when compared to the impacts which can occur due to a shortage of prototype hardware.

13. For contracted development programs, some non-deliverable prototypes, such as breadboards, do not add cost directly to the program. However, additional deliverable units obviously add moderate cost the the program.

14. Currently, prototype development programs are impacted by the reduced availability of U.S. component manufacturers as well as the scarcity of potential subcontractorts experienced with both medical and space hardware.

15. Maintenance and repair of equipment in long-duration applications is severely impacted by the current high rate of component obsolescence, early elimination of inventory and termination of factory support. Thus, an abundance of component parts, spares, and prototypes should be purchased with the initial contract.

16. Because of the impact of parts obsolescence problems on SSF equipment, consideration should be given to a shorter planned useful life cycle of perhaps 5 years.

17. The major limitation to reliability in high-quality, mass-produced equipment is component quality and the stochastic features of component tolerances.

18. The major limitations to reliability in high-quality equipment, produced in small quantities, are design imperfections and assembly/workmanship problems.

19. Since space flight hardware quantities are always small, major attention must be paid primarily to design and workmanship imperfections and secondarily to parts problems.

20. Class A equipment requires the highest reliability attainable. Therefore, maximum care must be applied to design refinement, workmanship, and component quality. In this case, Destructive Physical Analysis techniques being pioneered by DOD and DOE offer a potential for ensuring greater component consistency during component production runs continuing over long periods of time.

21. Prototype hardware development programs beginning from a new start can potentially make excellent use of modularization and commonality techniques. Special safeguards must be observed to prevent propagation of technical, schedule, and lifetime availability problems of the mandated module into each development program.

22. Prototype hardware development programs beginning from a new start are better suited than MCOTS programs for incorporation of automation techniques.

23. Exceptional NASA in-house technical knowledge and hands-on experience will facilitate increasing success in flight prototype hardware development and evaluation while providing conditions which yield developments at the lowest cost.

24. The interrelationships between the quantity drivers and other factors that should be used for the determination of the ideal quantities and types of prototypes that should be required of SBI hardware are too complex to model in a meaningful, yet simplistic, algorithm.

APPENDIX A

A PARTIAL LIST OF DOCUMENTS APPLICABLE TO SSF HARDWARE PROTOTYPING

ANSI/MIL-STD-1815A	Ada Language Reference Manual 22 Jan, 1983
ISO 7498/4	International Standardization Org.
JPL 86-14	The NASA Aerospace Battery Safety Handbook, 15 July, '86
JSC 31000	Product Assurance Requirements Volume 4
JSC SPEC M1	Specification Marking and Requirements Volume 4 4.9.1.1
JSC TBD	Space Station/NSTS Safety Identification, Vol. 4 2.1.4.1,2
JSCM 1700D	JSC Safety Manual, Vol. 4, 2.3
JSC 20527	Space Station EVA User Interfaces Design Guidelines Documentor 19 Nov. '86
JSC 20793	Manned Space Vehicle Battery Safety Handbook, Sept '85
JSC 21053	Space Station Program Payload Integration Plan
JSC 30213	Space Station Program Design Criteria and Practices. 15 Apr. '86
JSC 30233	Space Station Requirements for Materials and Processes 26 Nov. '86

JSC 30237	Space Station Electromagnetic Emission and Susceptibility Requirements for Electromagnetic Compatibility, 1 Dec '86
JSC 30238	Space Station Electromagnetic Techniques (MIL-STD-462 amended)
JSC 30240	Space Station Grounding Standard
JSC 30242	Space Station Cable/Wire Design and Control Standard
JSC 30243	Space Station Specification, System Electromagnetic Compatibility Requirements (MIL-E-6051D amended)
JSC 30244	Space Station Software Standards Document
JSC 30245	Space Station Electrical and Electronic Material and Process Standard
JSC 30425	Space Station Systems Requirement, Natural Environment Definition for Design, 15 Jan '87
JSC 31000	Product Assurance Requirements Volume 4
JSC 31011	WP-2 Master Verification Plan November '86
JSC 31013	Medical Requirements of an Inflight Medical System for Space Station, Revision A 30 Nov. '87
JSC 31016	FSE/OSE General Design Requirements, Nov. '86

JSC 31019	JSC Software Management Plan
JSC 31025	Acquisition Logistics Support Requirements
JSC 32015	Microbial Contamination
NSTS 07700	Space Shuttle Systems Payload Accommodations, Vol. 14, Revision J, 21 Oct. '86
KMI 1710.1	Safety, Reliability and Quality Assurance Program, Vol. 4, 2.1.6 and 4.1.3
MIL-HDBK-217	Reliability Prediction of Electronic Equipment, Vol. 4, 3.2.5.2
MIL-STD-105D	Sampling Procedures and Tables for Inspection by Attributes, Vol. 4, 4.11.1
MIL-STD-414	Sampling Procedures by Variables for Percent Defect, Vol 4, 4.11.1
MIL-STD-756	Reliability Modeling and Prediction, Vol. 4, 3.2.5.3
MIL-STD-970	Order of Precedence for the Selection of Standards and Specifications, Vol. 4, 3.3.2
MIL-STD-975	NASA Standard Electrical, Electronic and Electro-mechanical Parts List, Vol. 4, 3.3.1.2 and 3.3.1.4 and 3.3.1.6
NASA RP 1024	Anthropometric Source Book, Vol. 1 11 Nov., '86
NASA STD 3000	Man Systems Integration Standard Vol. 4, 21 Nov. '86

NHB 1700.1	Basic Safety Manual, Vol. 1A, 2.1.5 and 2.3 and 4.2.3
NHB 1700.1	System Safety, Vol. 3, 2.2.1
NSTS 07700	Space Shuttle Systems Payload Accommodations, Vol. 14, Revision J, 21 Oct. '86
SSP 30240	Space Station Grounding Standard Vol. 3
SSP 30257	Architectural Control Document Man-Systems: Revision B 15 June '88
NHB 1700.7A	Safety Policy and Requirements for Payloads Using the STS Vol. 4 2.2.2
SSP 30000	Product Assurance Requirements Section 9, Revision A 18 Mar '88
SSP 30309	Instructions for the Preparation of Hazard Analysis for the SSP Revision A, 15 Aug '88
SSP 30312	Electrical, Electronic and Electro-mechanical Parts Management and Implementation Plan for Space Station Jan '87
SSP 30233	Space Station Requirements for Materials Processing Vol. 4, 3.2.11
SSP 30234	Instructions for Preparation of FMEA/CIL For Space Station Vol. 4, 3.2.3
SSP 30309	Instructions for the Preparation of Hazard Analysis, Vol. 4, 2.2.3

SSP 30312	EEE Parts Management for Implementation Plan Vol. 4, 3.3.1.1 and 3.3.1.7 and 3.3.1.8
SSP 30313	Space Station Reliability/Maintainability Analysis, Vol. 4, 3.2.5
SSP 30423	Space Station Approved EEE Parts List (SSAEPL) Vol. 4, 3.3.1.2
SSP 30260	Architectural Control Document Communications and Tracking System Revision A,. Change 1, 5 Feb '88
SSP 30261	Architectural Control Document Data Management System, Revision B, Change 1, 19 Feb '88
SSP 30262	Architectural Control Document Environmental Control Life Support System, Revision B, 30 July '88
SSP 30263	Architectural Control Document Electrical Power System Revision B, Change 1, 19 Feb '88
SSP 30264	Architectural Control Document Fluid Management Systems Revision B, 15 Jan '87
SSP 30420	Space Station Electromagnetic, Ionizing Radiation and Plasma Environment Definition and Design Requirements, 15 Jan '87
SSP 30482	Space Station Electrical Power Characteristics, 5 May '87

APPENDIX B

PERSONAL INTERVIEWS AND OPINIONS

1. Aeivoli, Domonic; Program Manager for Commonality; General Electric Co., Philadelphia, PA. Telephone conversation covered wide range of flight hardware related subjects including: commercial communication satellites, earth resources (Landsat), and military satellites. Discussion included Protoflight type articles. He stressed that under all circumstances use of an engineering model prototype is essential.

2. Barnes, William J.; Design Engineering Manger, AT&T Technologies Systems: Burlington, NC. Mr. Barnes discussed use of prototypes in AT&T laboratory (was Bell Telephone Laboratory) development of guided missiles and commercial telephone equipment. He was unable to discuss exact details of under sea telephone signal repeater amplifiers for proprietary reasons. The laboratories utilize a large number of prototypes and extensive testing before building flight or commercial operational equipment.

3. Buckley, J.; Program General Manager, Science and Applications Programs, General Electric, Cherry Hills, NJ. Mr. Buckley discussed electronic parts problems and protoflight hardware programs. He described how program costs and schedules had been unfavorably impacted by lack of an engineering protoytpe model. His experience strongly demonstrates that it is essential to perform engineering development and thorough testing on prototype equipment prior to application of full R&QA formal documentation.

4. Burns, Frederick T., Jr.; Assistant Manager, Flight Support Equipment Office; Orbiter and GFE Projects Office Johnson Space Center. Mr. Burns provided extensive information on the rules, regulations, and procedures which must be complied with in order to fly equipment on the STS. He identified documents which greatly simplify and facilitate the process for hardware of certain types such as DTO and DSO programs.

5. Cubley, Dean, Ph.D.; Director of Engineering, Communications and Data Systems Associates, Webster, Texas. Dr. Cubley described how their company has been able to use computer

simulation in place of breadboard and brassboard prototypes in a protoflight development program. The single flight article will be used to conduct superconductivity experiments in space.

6. Evans, James S.; Technical Assistant, Life Sciences Project Division, Space and Life Sciences Office, Johnson Space Center. In two long and wide ranging meetings, Mr. Evans discussed many aspects of development programs for science and medical prototype equipment. He discussed both the good and bad experiences using the various techniques described in this study. He shared findings of a number of investigations he has conducted involving medical and science hardware used throughout all of NASA's manned space flight programs.

7. Fielder, George H.; Manager for Orbiter and GFE Projects; Safety, Reliability and Quality Assurance Office, Johnson Space Center. Mr. Fielder provided information related to the programmatic requirements imposed on flight hardware to be used on the Shuttle spacecraft. He also suggested individual persons to be contacted for specialized details and experiences.

8. Frey, Michael; Director, Mechanical Engineering; Intermedics Inc., Freeport, Tx. Mr. Frey's company is a world leader in the design and manufacture of implantable medical devices such as pacemakers and drug dispensers. Their products require the highest reliability attainable. He described their extensive and essential use of prototype development and test hardware. He described the effect of the parts availablilty problems on their company. It is now necessary for them to manufacture most of their components. With the exception of a few items such as batteries, they build all of their components including custom microcircuits and semiconductors.

9. Glanville, Roy W.; SSF Regulation Specialist; Reliability and Maintainability Division; Safety, Reliabililty and Quality Assurance Office, Johnson Space Center. Mr. Glanville provided an excellent insight into the documentation which will control every aspect of the design and application of flight hardware for the Space Station Freedom. He provided an understanding which allowed this study to identify the magnitude and complexity of the regulatory problem confronting any manufacturer wishing to design and build prototype and flight hardware for the SSF.

10. Goeke, Robert, Ph. D.; Center for Space Research, MIT, Cambridge MA. Dr. Geoke has had extensive experience in the design and fabrication of flight hardware for scientific investigations in space. Included are several pieces of LSLE equipment and astro physics payloads. He provided this study with much additional insight into the parts problems, the essential need for in-house design and hands-on hardware expertise, cost effective use of FMEAs, and many details which can boost reliability and flight article quantities while keeping costs at a minimum.

11. Graham, Olin L.; Section Head, Television Systems Section, Tracking and Communications Division, Engineering Directorate, Johnson Space Center. Mr. Graham provided details on prototype development programs, part problems, requirement documentation, and adaptation of commercial off-the-shelf hardware. Based on his extensive experience with flight hardware, he strongly recommended incorporation of numerous prototypes to achieve the greatest technical maturity possible.

12. Harlan, Charles S.; Director, Safety, Reliability & Quality Assurance Directorate, Johnson Space Center. The meeting with Mr. Harlan assisted in determining good contacts from which to obtain historical information. Part problems were discussed and he and his staff are interested in examining the potential benefits of Destructive Physical Analysis of semiconductor products.

13. Harris, Jackson D.; Technical Manager, Man-Systems Support, Lockheed Engineering. Mr. Harris assisted in understanding details of the Space Station Freedom programmatic technical requirements. Various subjects were discussed including which organizations and individuals could provide needed information on scientific instruments and their integration into SSF.

14. Holt, Aubry; Manager, Oil Equipment Systems Design; Smith International, Houston, Tx. Mr. Holt's company specializes in development and use of oil field instruments which operate under extremely adverse conditions of temperature, vibration, and pressure at the bottom of an oil well hole. Reliability is essential in their hardware. His insight into the parts problem, the use of development prototypes, and quality control testing contributed much pertinent new information.

15. Hymer, Robert L.; Manager, Nuclear Weapons Manufacturing Office, US Department of Energy, Albuquerque Operations Office, Albuquerque, NM. Mr. Hymer is responsible for nuclear weapons manufacturing in the United States and has an extreme interest in and understanding of reliable hardware development. He is an advocate of the use of numerous prototypes to develop device maturity before production. His insight into the parts problem led this study to the technique of Destructive Physical Analysis and the experts at Allied and Crane who perform it.

16. Kujawski, Peter; Chief, Re-Entry Systems, General Electric Company, Philadelphia, PA. Mr. Kujawski, who previously headed the GE Science and Applications Programs, is highly experienced in the development of reliable space flight hardware. He managed a massive protoflight program which produced the UARS (Upper Atmospher Research Satellite). His experience proves that it is extremely false economy to use too few prototype articles in a development program. He provided insight into the techniques of protoflight development.

17. Land, D. Kenneth; Chief, Tracking and Techniques Branch, Tracking and Communications Division, Engineering Directorate, Johnson Space Center, Houston, Tx. Mr. Land has extensive experience in all aspects of design and development of flight hardware. He has had notable success with modification of off-the shelf hardware. His identification of important details has contributed to the study.

18. Ramsey, Jim; Manager, Physical Analysis Laboratories, Naval Weapons Support Center, Crane, Indiana. Mr. Ramsey has a very great insight into all aspects of flight hardware reliability and production control. He contributed many details to this study. He and his personnel perform the Destructive Physical Analysis for DOD, DOE, and numerous private companies. They provided an understanding of the process and ways in which it may contribute to the SBI program.

19. Richards, Randall W.; Section Head, Command and Modulation Section, Tracking and Communications Division, Engineering Directorate, JSC. Mr. Richards has extensive experience in the development of GFE flight hardware. He is a strong advocate of ample prototype hardware. He assisted in understanding the

requirements placed on GFE flight hardware by the Shuttle program and clarified many points about the STS documentation tree. He provided very useful history of prototype development programs of all types.

20. Schulze, Arthur E.; Director, Biomedical Technologies Division; Lovelace Scientific Resources. Mr. Schulze provided some opinions on various aspects of designing and manufacturing medical and scientific equipment. During his career in the biomedical device industry, he has had the opportunity to optimize techniques for providing mature, reliable, hospital and space flight hardware. He has provided an historical perspective from the vendor's side of NASA's hardware programs which date back to the Skylab era.

21. Sinderson, Richard, Jr.; Section Head, Telemetry and Audio Section, Tracking and Communications Division Engineering Directorate, Johnson Space Center. Mr. Sinderson provided a myriad of facts describing the various methods by which NASA, JSC, has obtained much of its manned flight hardware from the time of Apollo on. His detailed procedures preserve much of the development technique for future developers to adapt for their needs.

22. Wilson, Burris G.; Engineering Manager, Kansas City Division Allied Signal Aerospace Company, Kansas City, Kansas. Mr. Wilson's organization performs many of the hardware development and manufacturing activities involved in equipping the nations weapons arsenals. He has provided information and contacts which have assisted this study in scoping the parts reliability problems. The Destructive Physical Analysis technique which he described is of interest to NASA's SR&QA personnel and will be explored by them for possible use by JSC.

APPENDIX C

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APPENDIX D

LIFE SCIENCES HARDWARE LIST

FOR THE

SPACE STATION FREEDOM ERA

H/W ITEM #	HARDWARE ITEM NAME	SOURCE CODE	UNIT HARDWARE PARAMETERS		
			VOLUME (cu. m)	MASS (kg)	POWER (watts)
1.8 METER CENTRIFUGE FACILITY (1)					
	SPECIMEN SUPPORT GROUP (1A)				
1	1.8 M Centrifuge	C	2.40	1100	1500
2	Equipment Washer/Sanitizer	W	0.96	320	2500
3	Life Sciences Glove Box (Copy 1 of 2)	W	0.96	350	800
4	Modular Habitat Holding System	C	0.48	200	500
5	Plant Growth Module	C	0.10	50	550
6	Primate Module	C	0.10	50	220
7	Rodent Module	C	0.07	40	230
BIOLOGICAL SAMPLE MANAGEMENT FACILITY (2)					
	BIOWASTE COLLECTION & MONITORING GROUP (2A)				
8	Fecal Monitoring System (24 Hr)	E	0.12	25	50
9	Urine Monitoring System (24 Hr)	E	0.20	60	50
	BIOLOGICAL SAMPLE STORAGE GROUP (2B)				
10	Freeze Dryer	W	0.07	19	140
11	Freezer (-20 deg. C)	W	0.48	120	300
12	Freezer (-70 deg. C)	W	0.48	120	300
13	Freezer Cryogenic (-196 deg. C) w/ Snap Freezer	W	0.09	20	0
14	Radiation Shielded Locker (Copy 1 of 2)	W	0.20	80	0
15	Refrigerator (4 deg. C)	W	0.48	120	300

source codes: C=1.8 CFP, S=SBI, E=EDCO, W=WP-01

H/W ITEM #	HARDWARE ITEM NAME	SOURCE CODE	UNIT HARDWARE PARAMETERS		
			VOLUME (cu. m)	MASS (kg)	POWER (watts)
BIOLOGICAL SAMPLE MANAGEMENT FACILITY (2), (con't)					
SAMPLE COLLECTION AND PROCESSING GROUP (2C)					
16	Animal Tissue Biopsy Equipment	S	0.03	8	0
17	Blood Collection System	S	0.02	1	0
18	Centrifuge Refrigerated	W	0.15	40	450
19	Centrifuge Standard Lab	E	0.09	26	200
20	Digital Thermometer	W	0.01	2	34
21	Drug Administration Equipment	E	0.01	1	0
22	Electrofusion Device	S	0.06	TBD	TBD
23	Fixation Unit	S	0.02	4	0
24	Fluid Handling Tools/System	W	0.48	80	100
25	Laboratory Sciences Workbench	W	0.96	300	700
26	Life Sciences Glove Box (Copy 2 of 2)	W	0.96	350	800
27	Microscope System (Stereo Macroscope Subset, Copy 2	W	0.25	80	200
28	Muscle Biopsy Equipment	S	0.01	1	0
29	Perfusion & Fixation Unit	S	0.01	2	0
30	Plant Care Unit	S	0.05	10	50
31	Plant Harvest/Dissection Unit	S	0.01	4	20
32	Radioimmunoassay Prep Device	E	0.01	2	0
33	Saliva Collection Unit	S	0.01	1	0
34	Sample Preparation Device	S	0.17	22	150
35	Shielded Isotope Container	E	0.02	22	0
36	Specimen Labeling Tools/Device	W	0.01	4	20
37	Surgery/Dissection Tools	W	0.06	20	0
38	Sweat Collection Device	S	0.01	TBD	0

source codes: C=1.8 CFP, S=SBI, E=EDCO, W=WP-01

H/W ITEM #	HARDWARE ITEM NAME	SOURCE CODE	UNIT HARDWARE PARAMETERS VOLUME (cu. m)	MASS (kg)	POWER (watts)
BIOLOGICAL SAMPLE MANAGEMENT FACILITY (2), (con't)					
	RODENT SUPPORT GROUP (2D)				
39	CO_2 Administration Device	S	0.01	3	0
40	Rodent Blood Collection System	S	0.03	10	50
41	Rodent Caudal Vertebrae Thermal Device (CVTD)	S	0.01	2	50
42	Rodent Guillotine	S	0.01	4	0
43	Rodent Restraint	S	0.01	3	0
44	Rodent Surgery Platform	S	0.01	3	0
45	Rodent Surgery/Dissection Unit	S	0.01	3	0
46	Rodent Urine Collection System	S	0.03	10	50
47	Rodent Veterinary Unit	S	0.03	10	0
	PRIMATE SUPPORT GROUP (2E)				
48	Primate Blood Collection System	S	0.05	2	140
49	Primate Handling Equipment	S	0.01	1	0
50	Primate LBNP Device	S	0.05	3	140
51	Primate Surgery Platform	S	0.04	5	0
52	Primate Surgery/Dissection Unit	S	0.02	5	0
53	Primate Urine Collection System	S	0.01	10	14
54	Primate Veterinary Unit	S	0.03	10	0
55	Small Primate Restraint	S	0.05	2	0

source codes: C=1.8 CFP, S=SBI, E=EDCO, W=WP-01

H/W ITEM #	HARDWARE ITEM NAME	SOURCE CODE	UNIT HARDWARE PARAMETERS		
			VOLUME (cu. m)	MASS (kg)	POWER (watts)
BIOINSTRUMENTATION & PHYSIOLOGICAL MONITORING FACILITY (3)					
PULMONARY ANALYSIS GROUP (3A)					
56	Bag Assembly	S	0.01	1	0
57	Bag-in-Box	S	0.15	19	0
58	Doppler Recorder	E	0.01	1	0
59	Electronics Control Assembly	S	0.08	13	100
60	Mask/Regulator System	S	0.01	3	30
61	Mass Spectrometer	S	0.02	10	100
62	Pulmonary Function Equipment Stowage Assembly	S	0.39	20	0
63	Pulmonary Gas Cylinder Assembly	S	0.09	30	0
64	Rebreathing Assembly	S	0.02	1	0
65	Spirometry Assembly	S	0.01	1	0
66	Syringe (3 Liter Calibration)	S	0.01	2	0
PHYSICAL MONITORING GROUP (3B)					
67	Accelerometer And Recorder	S	0.04	16	35
68	Anthropometric Measurement System	S	0.02	TBD	0
69	Cameras	W	0.15	50	150
70	Compliance Volumometer	S	0.06	TBD	TBD
71	Electroencephalomagnetogram (EEMG)	S	0.06	TBD	TBD
72	Electromyograph (EMG)	E	0.01	2	20
73	Force Measurement Device	E	0.01	1	10
74	Force Resistance System	S	0.40	70	100
75	Fundus Camera	S	0.03	TBD	TBD
76	Goniometer And Recorder	E	0.01	2	25

source codes: C=1.8 CFP, S=SBI, E=EDCO, W=WP-01

H/W ITEM #	HARDWARE ITEM NAME	SOURCE CODE	UNIT HARDWARE PARAMETERS VOLUME (cu. m)	MASS (kg)	POWER (watts)
BIOINSTRUMENTATION & PHYSIOLOGICAL MONITORING FACILITY (con't)					
	PHYSICAL MONITORING GROUP (3B) (con't)				
77	Hard Tissue Imaging System	S	0.29	136	300
78	Mass Calibration Unit	S	0.01	2	0
79	Mass Measurement Device-Body	E	0.65	35	15
80	Mass Measurement Device-Micro	W	0.08	17	15
81	Mass Measurement Device-Small	W	0.08	17	15
82	Motion Analysis System	S	0.05	20	100
83	Plethysmograph Measuring System	S	0.01	3	30
84	Soft Tissue Imaging System	S	0.96	300	800
85	Tonometer	S	0.01	TBD	0
86	Video System	E	0.10	30	300
	NEUROPHYSIOLOGICAL ANALYSIS GROUP (3C)				
87	EEG Cap	S	0.01	2	0
88	EEG Signal Conditioner	S	0.01	2	20
89	Electrode Impedance Meter	E	0.01	1	0
90	Electro-oculograph (EOG)	E	0.01	2	20
91	Neurovestibular ECDI	E	0.09	11	120
92	Neurovestibular Helmet Interface Box	E	0.01	2	20
93	Neurovestibular Helmet Assembly	E	0.04	13	110
94	Neurovestibular Helmet Restraint	E	0.01	2	20
95	Neurovestibular Optokinetic Stimulus	E	0.01	2	20
96	Neurovestibular Rotating Chair	E	0.12	38	220
97	Subject Restraint System	E	0.05	18	0
98	Visual Tracking System	S	0.01	2	20

source codes: C=1.8 CFP, S=SBI, E=EDCO, W=WP-01

H/W ITEM #	HARDWARE ITEM NAME	SOURCE CODE	UNIT HARDWARE PARAMETERS VOLUME (cu. m)	MASS (kg)	POWER (watts)
BIOINSTRUMENTATION & PHYSIOLOGICAL MONITORING FACILITY (con't)					
	CARDIOVASCULAR GROUP (3D)				
99	Animal Biotelemetry System	S	0.05	20	100
100	Blood Pressure And Flow Instrumentation	S	0.06	20	200
101	Cardiodynamic Monitor	S	0.02	4	150
102	Electrocardiograph (ECG)	S	0.01	2	20
103	Holter Recorder	S	0.01	2	0
104	Human Biotelemetry System	E	0.05	17	140
105	LBNP Device	E	0.16	20	55
106	Neck Baro-Cuff	S	0.10	TBD	TBD
107	Physiological Hemodynamic Assess Device	E	0.05	18	100
108	Ultrasonic Imaging System	W	0.20	70	600
109	Venous Pressure Transducer/Display	S	0.05	20	100
	PLANT MONITORING GROUP (3E)				
110	Plant Gas Chromatograph/Mass Spectrometer	S	0.20	25	100
111	Plant Gas Cylinder Assembly	S	0.09	19	0
112	Plant HPLC Ion Chromatograph	S	0.12	40	200

source codes: C=1.8 CFP, S=SBI, E=EDCO, W=WP-01

H/W ITEM #	HARDWARE ITEM NAME	SOURCE CODE	UNIT HARDWARE PARAMETERS VOLUME (cu. m)	MASS (kg)	POWER (watts)
ANALYTICAL INSTRUMENTS FACILITY (4)					
BIOLOGICAL SAMPLE ANALYSIS GROUP (4A)					
113	Blood Gas Analyzer	S	0.13	45	250
114	Chemistry Analysis System	E	0.10	30	200
115	Chemistry System	S	0.08	23	100
116	Continuous Flow Electrophoresis Device	S	0.06	TBD	TBD
117	ELISA Reader	E	0.02	6	100
118	Gas Chromatograph/Mass Spectrometer	W	0.20	25	100
119	Gas Cylinder Assembly	S	0.09	19	0
120	High Performance Liquid Chromatograph	W	0.12	40	100
121	Incubator (35-65 deg C Copy 1 of 2)	W	0.16	50	400
122	Osmometer	E	0.02	5	20
123	pH Meter/Ion Specific Analyzer	W	0.02	7	5
124	Qualitative Reagent Strip And Reader	S	0.03	10	100
125	Radioimmunoassay	E	0.05	20	0
126	Scintillation Counter	S	0.24	90	500
127	Spectrophotometer (UV/VIS/NIR)	W	0.11	40	300
128	Urine Analysis System	E	0.16	55	400
CELL ANALYSIS GROUP (4B)					
129	Cell Handling Accessories	S	0.05	20	50
130	Cell Harvestor	S	0.06	19	50
131	Cell Perfusion Apparatus	S	0.06	TBD	TBD
132	Centrifugal Incubator (5% CO2 @37 deg C Copy 1 of 2)	E	0.16	40	300
133	Centrifugal Incubator (5% CO2 @37 deg C Copy 2 of 2)	E	0.16	40	300

source codes: C=1.8 CFP, S=SBI, E=EDCO, W=WP-01

H/W ITEM #	HARDWARE ITEM NAME	SOURCE CODE	UNIT HARDWARE PARAMETERS VOLUME (cu. m)	MASS (kg)	POWER (watts)
ANALYTICAL INSTRUMENTS FACILITY (4) (con't)					
	CELL ANALYSIS GROUP (4B) (con't)				
134	Centrifuge Hematocrit	S	0.01	2	20
135	Chromosomal Slide Preparation Device	S	0.01	2	20
136	Fluoromeasure Probe	S	0.05	TBD	TBD
137	Flow Cytometer	E	0.24	36	500
138	Hematology System	S	0.07	23	200
139	Image Digitizing System	S	0.25	70	500
140	Microscope System (Optical & Stereo Macroscope Subsets)	W	0.40	100	400
141	Mitogen Culture Device	E	0.01	2	20
142	Skin Window Device	S	0.01	2	0
143	Slide Preparation Device	E	0.01	2	20

H/W ITEM #	HARDWARE ITEM NAME	SOURCE CODE	UNIT HARDWARE PARAMETERS		
			VOLUME (cu. m)	MASS (kg)	POWER (watts)
LAB SUPPORT EQUIPMENT FACILITY (5)					
ENVIRONMENTAL MONITORING & CONTROL GROUP (5A)					
144	Accelerometer Subsystem	W	0.10	30	200
145	Automated Microbic System	S	0.20	70	500
146	Dosimeter, Passive	W	0.09	35	0
147	Head/Torso Phantom	S	0.12	TBD	0
148	Incubator (35-65 deg C Copy 2 of 2)	W	0.16	50	400
149	Microbial Preparation System	S	0.01	2	20
150	Radiation Shielded Locker (Copy 2 of 2)	W	0.20	80	0
151	Reuter Microbiology Air Sampler	S	0.01	1	0
152	Solid Sorbent Air Sampler	S	0.01	5	0
153	Spectrometer (Proton/Heavy Ion)	S	0.03	10	20
154	Tissue Equivalent Proportional Counter	S	0.01	TBD	0
155	Total Hydrocarbon Analyzer	S	0.20	70	250
HARDWARE MAINTENANCE GROUP (5B)					
156	Battery Charger	W	0.03	10	100
157	Camera Locker	W	0.30	100	0
158	Cleaning Equipment	W	0.20	70	500
159	Digital Multimeter	W	0.06	20	50
160	General Purpose Hand Tools	W	0.10	30	0
LOGISTICS CONTROL GROUP (5C)					
161	Inventory Control System	S	0.20	70	500
162	Lab Materials Packaging & Handling Equipment	S	0.20	70	500
163	Test/Checkout/Calibration Instrumentation	S	0.20	70	200

source codes: C=1.8 CFP, S=SBI, E=EDCO, W=WP-01

H/W ITEM #	HARDWARE ITEM NAME	SOURCE CODE	UNIT HARDWARE PARAMETERS		
			VOLUME (cu. m)	MASS (kg)	POWER (watts)
CENTRALIZED LIFE SCIENCES COMPUTER FACILITY (6)					
	LIFE SCIENCES DATA GROUP (6A)				
164	Digital Recording Oscilloscope	W	0.03	10	100
165	Experiment Control Computer System	S	0.05	20	400
166	Multichannel Data Recorder	E	0.09	30	150
167	Voice Recorder	S	0.01	1	0
CLOSED ECOLOGICAL LIFE SUPPORT FACILITY (7)					
	FEAST GROUP (7A)				
168	CELSS Test Facility	S	1.92	1000	1300
EXOBIOLOGY FACILITY (8)					
	GAS/GRAIN GROUP (8A)				
169	Gas Grain Simulator	S	1.92	800	1500

source codes: C=1.8 CFP, S=SBI, E=EDCO, W=WP-01

LIFE SCIENCES HARDWARE BA LINE, REV 1, DEFINITIONS

1.8 M Centrifuge	A device designed to produce a gravity gradient on plants, rodents and small primates, providing a 1g control for microgravity experiments.
Accelerometer Subsystem	A system of vectored accelerometers with interfaces to data recording and data processing, monitoring three-axis microgravity levels in the range of 1 E-7g to 1g within the U. S. Laboratory Module. Source: SS-SPEC-0002.
Accelerometer and Recorder	Measures and records the rate of change of velocity of an object, i.e., forward linear motion or vibration detection.
Animal Biotelemetry System	A set of sensors and transducers to monitor various physiological parameters of animal specimens.
Animal Tissue Biopsy Equipment	Set of specialized instruments to perform tissue studies on animal specimens.
Automated Microbic System	An instrument capable of identifying microbes based upon the automated analysis of changes in color or turbidity within incubated reaction chambers.
Bag Assembly	Re-breathing bag; part of the Pulmonary Function hardware set, used to measure lung function and capacity in microgravity.
Bag-in-Box	Part of the Pulmonary Function hardware set, used to measure lung function and capacity in microgravity.
Battery Charger	A compact device for recharging nickel cadmium batteries that are used in a number of small instruments (e.g. digital thermometers, digital multimeters) or payloads.
Blood Collection System	Blood collection items that can be used more than once. Includes vacutainer holders and tourniquets.
Blood Gas Analyzer	Instrument for detecting and measuring the amount of dissolved gases in blood, usually carbon dioxide.and oxygen.
Blood Pressure And Flow Instrumentation	Instrumentation for measuring arterial blood pressure and flow.

LIFE SCIENCES HARDWARE BA :LINE, REV 1, DEFINITIONS

Camera Locker	Provides equipment storage space for cameras, accessories and associated components, to include lights, mountings, hardware, etc.
Cameras	Still and video cameras for general laboratory photography.
Cardiodynamic Monitor	Determines cardiac output by measuring changes in regional (thoracic) impedance.
Cardiopulmonary Analyzer Flowmeter	Measures oxygen uptake, carbon.dioxide production and heart rate as it relates to total pulmonary ventilation.
Cell Handling Accessories	Tools used to transfer cells from specimens to microscope slides in a microgravity environment.
Cell Harvester	Used to isolate cells from a large sample and deposit isolated cells into a chamber for further analysis.
CELSS Test Facility	A testbed experiment for the Controlled Ecological Life Support System, intended to test the feasibility of a self-sustaining life support system in microgravity.
Centrifugal Incubator (5% CO2 @37 deg. C Copy 1 of 2)	A centrifuge, producing a 1g radial acceleration, with a set temperature of 37 degrees C and a carbon dioxide-rich atmosphere. This centrifuge will provide 1g control for tissue culture studies.
Centrifugal Incubator (5% CO2 @37 deg. C Copy 2 of 2)	Identical to above centrifuge (copy 1) except that the spinning function is disabled, for use in tissue culture studies.
Centrifuge Hematocrit	A specialized centrifuge for separating plasma from formed elements in blood samples.to determine hematocrit
Centrifuge Refrigerated	Uses centrifugal acceleration to separate materials by density in a temperature controlled environment.
Centrifuge Standard Lab	An instrument which provides centrifugal acceleration for separation or processing of liquid samples in hematology,microbiology and immunology.

LIFE SCIENCES HARDWARE BASELINE, REV 1, DEFINITIONS

Chemistry Analysis System	An instrument which employs liquid reagents to measure various components of serum, plasma, and urine. The system includes provisions for sample pick-up, sample delivery, protein separation, reagent addition, mixing, incubation, reaction detection and data presentation.
Chemistry System	An instrument primarily used to determine the levels of compounds in blood and urine (e.g. urea, glucose, calcium, etc).
Chromosomal Slide Preparation Device	A device used to prepare microscope slides in a manner such that the chromosomes can be properly observed.
Cleaning Equipment	Tools and supplies necessary to perform housekeeping and cleanup of laboratory equipment, to include interior surfaces of gloveboxes.
CO2 Administration Device	A device used to quantitatively increase the amount of CO2 inspired by either rodents or primates.
Digital Multimeter	General purpose hand-held voltage, current and resistance meter for use in maintenance and adjustment of electric/electronic equipment, and for temporary service in ad hoc experiments.
Digital Recording Oscilloscope	Instrument for detecting, digitizing, recording and displaying periodic and transient electrical waveforms for use in electronic maintenance and experiment calibration.
Digital Thermometer	Portable, hand-held temperature measurement system for spot checking and fault diagnosis in experiment systems, as well as for temporary service in ad-hoc experiments.
Doppler Recorder	Portable data recorder to record blood flow as monitored from doppler blood flow instrumentation.
Dosimeter Passive	A small badge (Thermoluminescent Dosimeter or TLD) used to monitor various forms of radiation. The TLD badge is read by placing it in a reader/annealer, specifically designed for this purpose. The badge emits light upon heating in proportion to radiation exposure; this release of energy in the form of light returns the badge to a ready-to-use condition.

LIFE SCIENCES HARDWARE BASELINE, REV 1, DEFINITIONS

Drug Administration Equipment	Equipment for the administration of various drugs to include oral, IV and rectal administration.
EEG Cap	A cap fitted with appropriate electrodes for the measurement and recording of brain electrical activity.
EEG Signal Conditioner	Instrumentation to provide biopotential signal amplification and conditioning.
Electro-Magnetic Tendon Striker	A device used to stimulate the contraction of voluntary muscle groups.
Electro-oculograph (EOG)	A device used to monitor the electrical activity of the muscles controlling eye movement.
Electrocardiograph (ECG)	Measures, records and displays the electrical activity of the heart.
Electrode Impedance Meter	An instrument used to measure impedance between electrodes (particularly EOG) to ensure signal quality.
Electromyograph (EMG)	A device used to monitor the electrical activity of skeletal muscles during contraction.
Electronics Control Assembly	Part of the Pulmonary Function hardware, which controls the mixture of gases introduced to the subject through the Bag Assembly.
ELISA Reader	Enzyme Linked Immuno-Sorbent Assay spectrophotometer. A device to record the change in spectral absorbance within the wells of an ELISA microtiter plate, with time, either single event, continuously or at frequent intervals, thus allowing kinetic measurements to be made.
Equipment Washer/Sanitizer	Device to clean and sanitize laboratory equipment, to include tools, animal cages, plant cuvettes, etc.
Experiment Control Computer System	Basic Life Sciences computer system to provide buffer memory and mass storage capability and interface between experiment hardware and the data management system.
Fecal Monitoring System (24 Hr)	Provides for fecal collection and measurement and allows for sample extraction.

Fixation Unit	A selection of biological dyes, fixatives and ancillary hardware necessary for sample preparation and preservation in a microgravity environment.
Flow Cytometer	An instrument which uses optical methods to count, measure and analyze individual cell characteristics.
Fluid Handling Tools/System	A system capable of handling bodily fluids and chemicals/reagents and be capable of measuring, separating, mixing, transferring, distributing and disposing of these liquids.
Force Measurement Device	A series of sensors capable of measuring force to be attached to various places on the body or to be used to monitor muscle force production.
Force Resistance System	A device to provide either positive or negative forces to counter muscle activity (either isometrically, isotonically or isokinetically) and measure force production during each case.
Freeze Dryer	Device which dehydrates samples by freezing them in a high vacuum.
Freezer (-20 deg. C)	Freezer which maintains -20 deg C.
Freezer (-70 deg. C)	Freezer which maintains -70 deg.C.
Freezer Cryogenic (-196 deg. C) w/ Snap Freezer	Freezer which incorporates a preliminary freezer to quick-freeze a specimen before storage to allow the main freezer to maintain a very low temperature.
Gas Chromatograph/Mass Spectrometer	(GC/MS) Identifies a substance by sorting a stream of electrified particles (ions) according to their volatility and/or mass. Monitors inspired and expired gases, and oxygen uptake to determine metabolic rate, etc.
Gas Cylinder Assembly	Several cylinders containing gases required for the operation of GC/MS, as well as Pulmonary Function Hardware (The gases required for each are different gases).
Gas Grain Simulator	Hardware used to analyze the interactions between gases and very fine particles in a microgravity environment.

General Purpose Hand Tools	Tools required for general and/or minor maintenance of laboratory hardware.
Goniometer And Recorder	An instrument used to measure the range of motion of joints (angles) of crew members in microgravity.
Hard Tissue Imaging System	An instrument which produces two-dimensional images of dense tissues.
Hematology System	A device which performs red, white, and platelet cell counts, hemoglobin concentrations and other hematological measurements.
High Performance Liquid Chromatograph	Separates and identifies components of a solution by virtue of their differences in sign and magnitude of charge. It is capable of such functions as: high pressure liquid, gel permeation, reverse phase, and size exclusion chromatography.
Holter Recorder	Recorder used to monitor cardiac function by recording the analog signals produced by a continuous ECG.
Human Biotelemetry System	A set of sensors and transducers to monitor various physiological parameters of human subjects.
Image Digitizing System	Converts images from any source into digital form, performs limited pattern recognition, and transfers digital data from Space Station to ground communications.
Incubator (35-65 deg C Copy 1 of 2)	An enclosure used to provide proper atmospheric conditions required to grow biological specimens and microorganisms.
Incubator (35-65 deg C Copy 2 of 2)	Same as above.
Inventory Control System	Device to enter, monitor and control items in the current inventory, including biological specimens.
Isokinetic Measurement Device	Measures the resistive force of muscle at various points of motion with controlled force and compression determinations.

Lab Materials Packaging & Handling Equipment	System that provides for the transfer of biological materials (e.g. tissue samples, biological reagents), while maintaining bio-isolation from the crew.
Laboratory Sciences Workbench	A bench (or table top) where samples not requiring bioisolation can be prepared for storage or analysis.
LBNP Device	A Lower Body Negative Pressure device used to direct blood from the upper extremities to the lower extremities in a controlled manner.
Life Sciences Glove Box (Copy 1 of 2)	A bio-isolated compartment used for the manipulation of biological specimens and samples, specifically those associated with plant and animal studies.
Life Sciences Glove Box (Copy 2 of 2)	A bio-isolated compartment used for the manipulation of biological specimens and samples, specifically those associated human-oriented studies.
Mask/Regulator System	Part of the Pulmonary Function hardware complement which provides the crew interface.
Mass Calibration Unit	Set of known masses to calibrate onboard mass measuring devices.
Mass Measurement Device-Body	A device used to determine the mass of human subjects in microgravity.
Mass Measurement Device-Micro	A device used to determine the mass of specimens having a mass less than 1 mg in microgravity.
Mass Measurement Device-Small	A device used to determine the mass of specimens in the range of 1 mg to 10,000 gm in microgravity.
Mass Spectrometer	An instrument used to determine components of a solution or gas by analyzing the molecular fragments according to their atomic mass.
Microbial Preparation System	A system which automatically prepares microbial samples for analysis in the Automated Microbic System.
Microscope System (Optical & Stereo Macroscope Subsets)	LSE hardware which provides the functions of an optical microscope and stereo macroscope.

Microscope System (Stereo Macroscope Subset, Copy 2 of 2)	Stereo macroscope to be used for dissection of various biological specimens.
Mitogen Culture Device	A device which bathes incubated cells in a mitogen-rich environment to stimulate mitosis.
Modular Habitat Holding System	A system which accommodates the modular habitats used to house live animal subjects.
Motion Analysis System	Video system used to monitor, record and analyze the motion of crew members during weightlessness.
Multichannel Data Recorder	A recorder which can accept and condition signals from various physical parameters, simultaneously.
Muscle Biopsy Equipment	Tools and instruments required to harvest tissue specimens from rodents and primates.
Neurovestibular ECDI	Experiment Control and Data Interface, a computer-based system that controls and collects data from hardware used in neurovestibular investigations.
Neurovestibular Helmet Interface Box	Contains EOG signal conditioner that transmits analog signals to the ECDI.
Neurovestibular Helmet Assembly	Highly-modified "motorcycle helmet", instrumented and equipped for neurovestibular studies.
Neurovestibular Helmet Restraint	Attaches Helmet to the rotating chair.
Neurovestibular Optokinetic Stimulus	Part of the NV helmet assembly which provides the stimulus.
Neurovestibular Rotating Chair	Chair which revolves at different frequencies in two directions.
Osmometer	Measures the concentration of dissolved particles in a solution.
Perfusion & Fixation Unit	A set of chemicals and ancillary hardware required to treat and preserve tissue samples for later examination and study.

ph Meter/Ion Specific Analyzer	An instrument used to measure the acid-base status of various sample types, and with ion-specific electrodes, can measure the ionic concentration of the sample.
Physiological Hemodynamic Assess Device	Device used to measure Central Venous Pressure non-invasively. It utilizes a respiratory flow and pressure meter, in conjunction with doppler, ultrasound.
Physiological Monitoring System	An instrument, similar to a patient monitor, which monitors the cardiovascular system (heart rate, blood pressure, electrocardiograph, body temperature, etc.)
Plant Care Unit	Hardware required for the daily care and maintenance of plant in a microgravity environment.
Plant Gas Chromatograph/Mass Spectrometer	Identifies a substance by sorting a stream of electrified particles (ions) according to their volatility and/or mass, specifically designed for use in plant studies.
Plant Gas Cylinder Assembly	Gases used to support the Plant Gas Chromatograph/Mass Spectrometer.
Plant Growth Module	Container wherein plants will be grown in microgravity.
Plant Harvest/Dissection Unit	A set of specialized instruments to gather and dissect plant specimens.
Plant HPLC Ion Chromatograph	Separates and identifies components of a solution by virtue of their differences in sign and magnitude of charge, specifically designed for monitoring plant specimens.
Plethysmograph Measurement System	A system for measuring and recording the changes in volume of an organ, part or limb and the amount of blood present or passing through it.
Primate Blood Collection System	A system to safely collect sterile blood samples from primate subjects.
Primate Handling Equipment	A set of specialized equipment to be used to safely handle primate specimens in a microgravity environment.
Primate LBNP Device	A device for applying a negative atmospheric pressure to the lower extremities of a primate subject.

Primate Module	Container wherein primates will be housed in microgravity.
Primate Surgery Platform	A device used to restrain a primate in positions suitable for surgery.
Primate Surgery/Dissection Unit	Tools required (e. g. scalpels, sutures, etc.) for the surgery and dissection of primates.
Primate Urine Collection System	A system to safely collect sterile urine samples from primate subjects.
Primate Veterinary Unit	A set of instruments and other required materials to ensure the health and safety of primate subjects.
Pulmonary Function Equipment Stowage Assembly	A unit which safely stows the portion of the Pulmonary Function Equipment which is not rack mounted.
Pulmonary Gas Cylinder Assembly	A set of compressed gas cylinders containing gases of known composition, used in support of the Pulmonary Function hardware.
Pulmonary Monitoring System	A instrument capable of monitoring human pulmonary function, such has total lung volume, reserve, tidal volume, maximum O_2 cosumption, etc.
Qualitative Reagent Strip And Reader	A device that will qualitatively assess levels of compounds or ions (e.g. hydrogen ions, glucose, urea, calcium) present in animal blood or urine.
Radiation Shielded Locker (Copy 1 of 2)	A locker for the storage of items which will be degraded if exposed to ionizing radiation.
Radiation Shielded Locker (Copy 2 of 2)	A locker which will accommodate radioactive items which require isolation.
Radioimmunoassay Prep Device	A device which would prepare blood or urine samples,for an immunological procedure in which hormones, antigens, antibodies, drugs and other substances occurring in minute quantities are measured using radioisotopes.
Radioimmunoassay	A device in which hormones, antigens, antibodies, drugs and other substances occurring in minute quantities are measured using radioisotopes.

LIFE SCIENCES HARDWARE BASELINE, REV 1, DEFINITIONS

Rebreathing Assembly	Pulmonary Function support equipment. Collects and measures exhaled air for rebreathing by subject.
Refrigerator (4 deg. C)	An insulated unit capable of storing various materials at 4 deg. C
Reuter Microbiology Air Sampler	A hand held centrifugal air sampler which collects microorganisms upon specific growth media.
Rodent Blood Collection System	A system to safely collect sterile blood samples from rodent subjects.
Rodent Caudal Vertebrae Thermal Device (CVTD)	A device used to warm the tails of rodents in a microgravity environment.
Rodent Guillotine	Device for the humane decapitation of rodent specimens.
Rodent Module	Container wherein rodents will be housed in microgravity.
Rodent Restraint	A device to safely hold a rat subject during handling.
Rodent Surgery Platform	A device used to restrain a rodent in positions suitable for surgery.
Rodent Surgery/Dissection Unit	Tools required (e. g. scalpels, sutures) for the surgery and dissection of rodents.
Rodent Urine Collection System	A system to safely collect sterile urine samples from rodent subjects.
Rodent Veterinary Unit	A set of instruments and other required materials to ensure the health and safety of rodent subjects.
Saliva Collection Unit	A device to safely collect saliva specimens from human subjects.
Sample Preparation Device	A device which will prepare various biological samples for subsequent analysis, which includes the addition of required reagents.
Scintillation Counter	Measures the light emitted when an x-ray or gamma ray is absorbed by a crystal or liquid radiation detector. It is based on the principal that exposure of certain materials to ionizing radiation results in the conversion of the kinetic energy of the particles or photons into the flashes of light or scintillations.

Shielded Isotope Container	A container for storing isotopes which inhibits the transmission of ionizing radiation.
Skin Window Device	A device which is applied to the surface of the skin to facilitate the collection and analysis of skin cells.
Slide Preparation Device	An automated device to fix and stain micro-organisms and blood
Small Primate Restraint	A device to safely hold a small primate subject during handling.
Soft Tissue Imaging System	A system which provide a two dimensional image of organs and other soft tissues.
Solid Sorbent Air Sampler	An air sampler that continuously deposits trace level air contaminants for lab analysis.
Specimen Labeling Tools/Device	A device capable of automatically labeling containers and specimens, which can be automatically read and entered into a database which contains all the information pertaining to that particular sample or specimen.
Spectrometer (Proton/Heavy Ion)	A device which measures protons from the trapped belts, heavy ions, and fragmented particles of heavy ions.
Spectrophotometer (UV/VIS/NIR)	An instrument capable of quantitatively measuring light-absorbing components in a solution.
Spirometry Assembly	Part of the Pulmonary Function support hardware which measures air inhaled and exhaled from the lungs.
Subject Restraint System	A system which immobilizes part or all of a human subject.
Surgery/Dissection Tools	Tools and instruments necessary for surgery or dissection of either rodents or primates.
Syringe (3 Liter Calibration)	Pulmonary Function support equipment which is used to calibrate the Bag-in-Box.
Test/Checkout/Calibration Instrumentation	Self explanatory.

Total Hydrocarbon Analyzer	An instrument used to measure the total hydrocarbon content in biological samples.
Turbidity Meter	A device which measures the degree of cell growth by measuring the turbidity of the cell media.
Ultrasonic Imaging System	Provides images for the visualization of deep structures of the body by recording the reflections of pulses of ultrasonic waves directed into the tissues.
Urine Analysis System	A system which provides for the analysis of urine samples in the microgravity environment.
Urine Monitoring System (24 Hr)	A system for the collection, storage, preservation and measurement of human urine samples in a microgravity environment.
Venous Pressure Transducer/Display	Transducers and displays used to measure central venous pressure, via the insertion of a catheter into either the right atrium or the vena cava.
Video System	System used to record the video images received from video cameras.
Visual Tracking System	Monitors and record eye movements during neurovestibular studies.
Voice Recorder	A hand-held device used to record crew voices during experiment procedures.